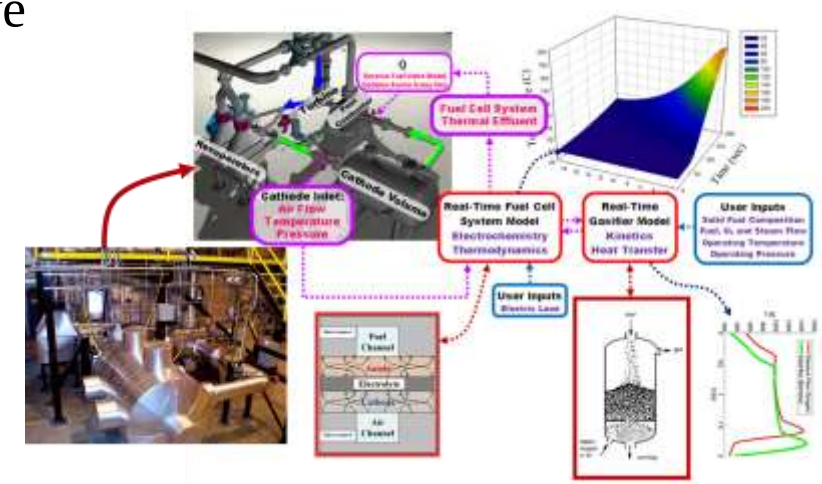
Controls Development for Hybrid Systems
Dr. David Tucker, NETL

Project Vision

- We are completing system analyses required for the operable design of two representative systems: FC/GT and FC/ICE.

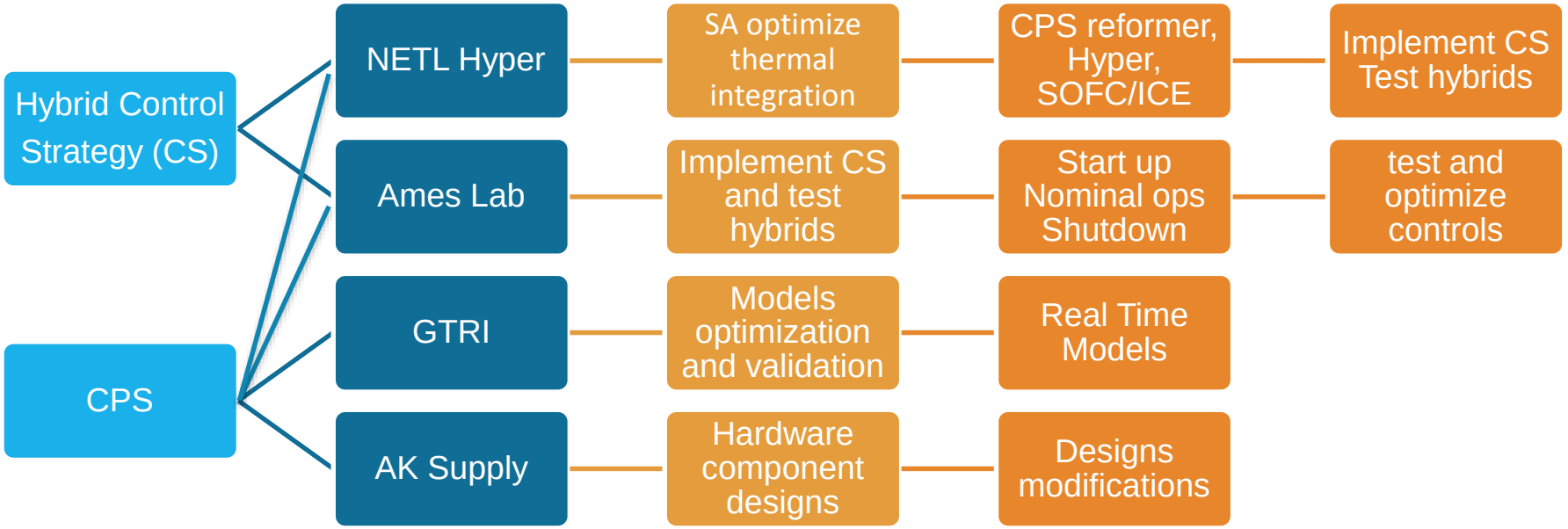
- We are developing and testing both supervisory control and dynamic control algorithms in advance of the fabrication of proposed cycles using NETL's cyber-physical systems.



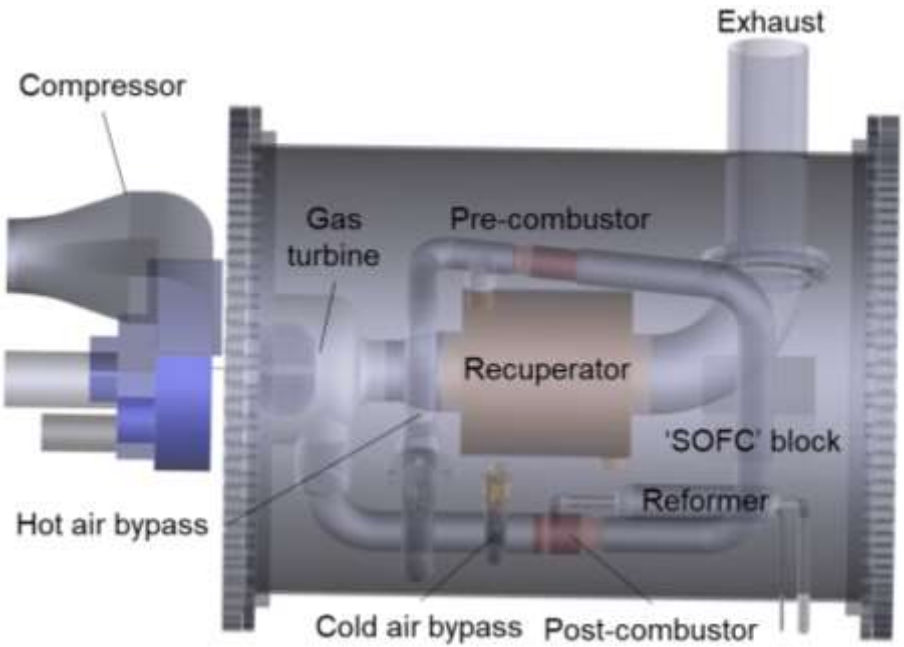
Project Overview

Fed. funding:	$1.7 M
Length	24 mo.

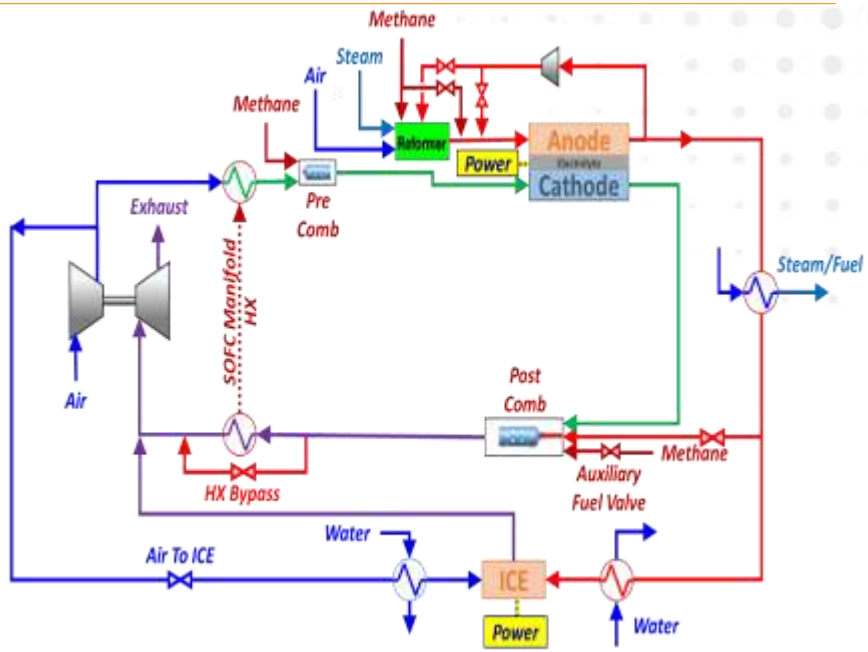
Team member	Location	Role in project
National Energy Technology Laboratory (NETL)	Morgantown, WV	Project Lead; Cycle Evaluation; Cyber-Physical System Designs
Ames Laboratory (Ames)	Ames, IA	Operational Control Strategy and Dynamic Controls Development
Georgia Tech Research Institute (GTRI)	Atlanta, GA	Cycle Evaluation; Cyber-Physical Design and Construction
AK Supply, Inc.	Anchorage, AK	Design and Construction



Innovation and Objectives



Layout for the CPS reformer



Potential Cycle Modifications

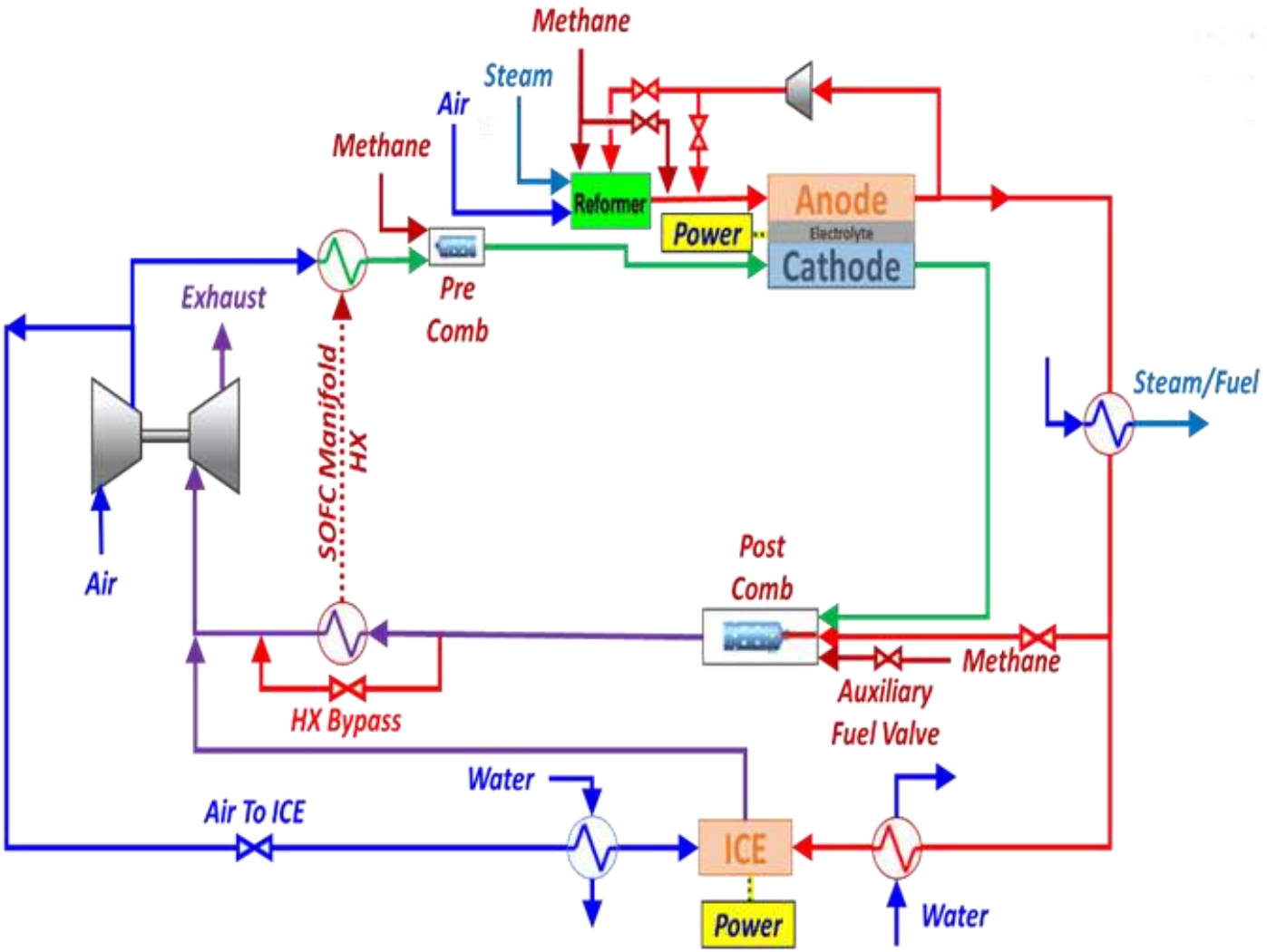
Task outline, technical objectives

Development of control strategies applicable to both SOFC/GT and SOFC/ICE hybrid power systems using a cyber-physical approach

Tech-to-Market objectives

- Support the other teams by ensuring viable dynamic and supervisory control strategies

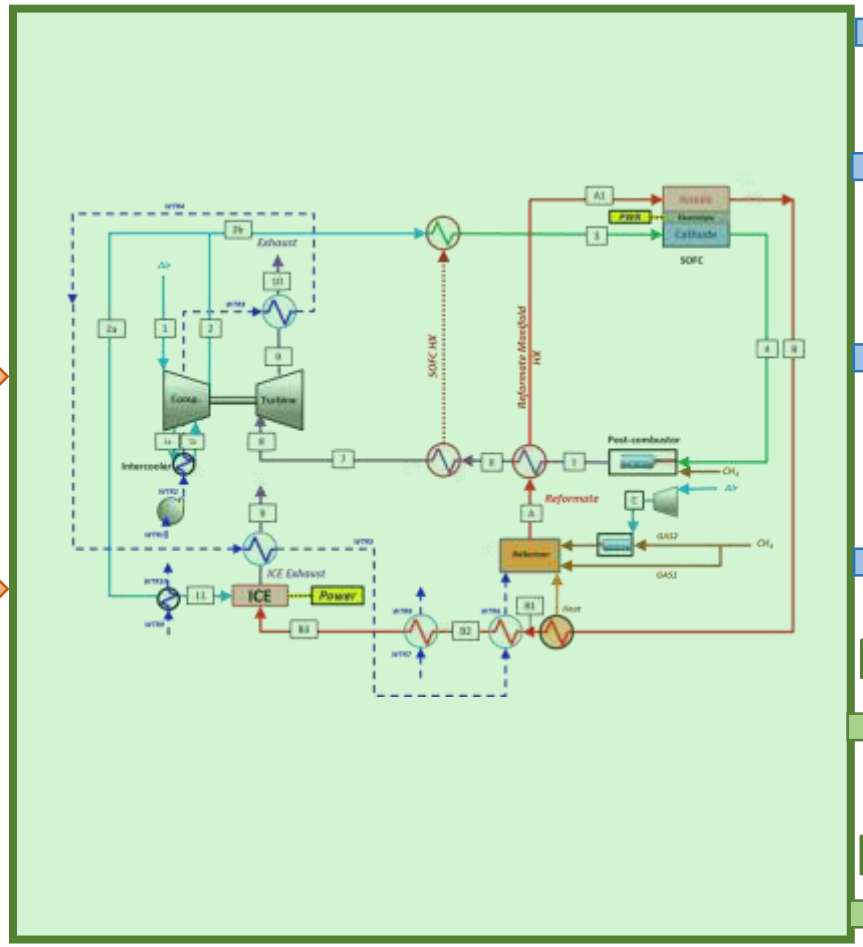
FC/ICE Hybrid Cycle Evaluation



FC/ICE Hybrid Cycle Evaluation

LHV-FC Fuel

LHV-C1 Fuel



GT Exhaust $\dot{m}\int_{T_R}^{T} C_p dT$

ICE Exhaust $\dot{m}\int_{T_R}^{T} C_p dT$

ICE Inlet Air Cooling $\dot{m}\int_{T_R}^{T} C_p dT$

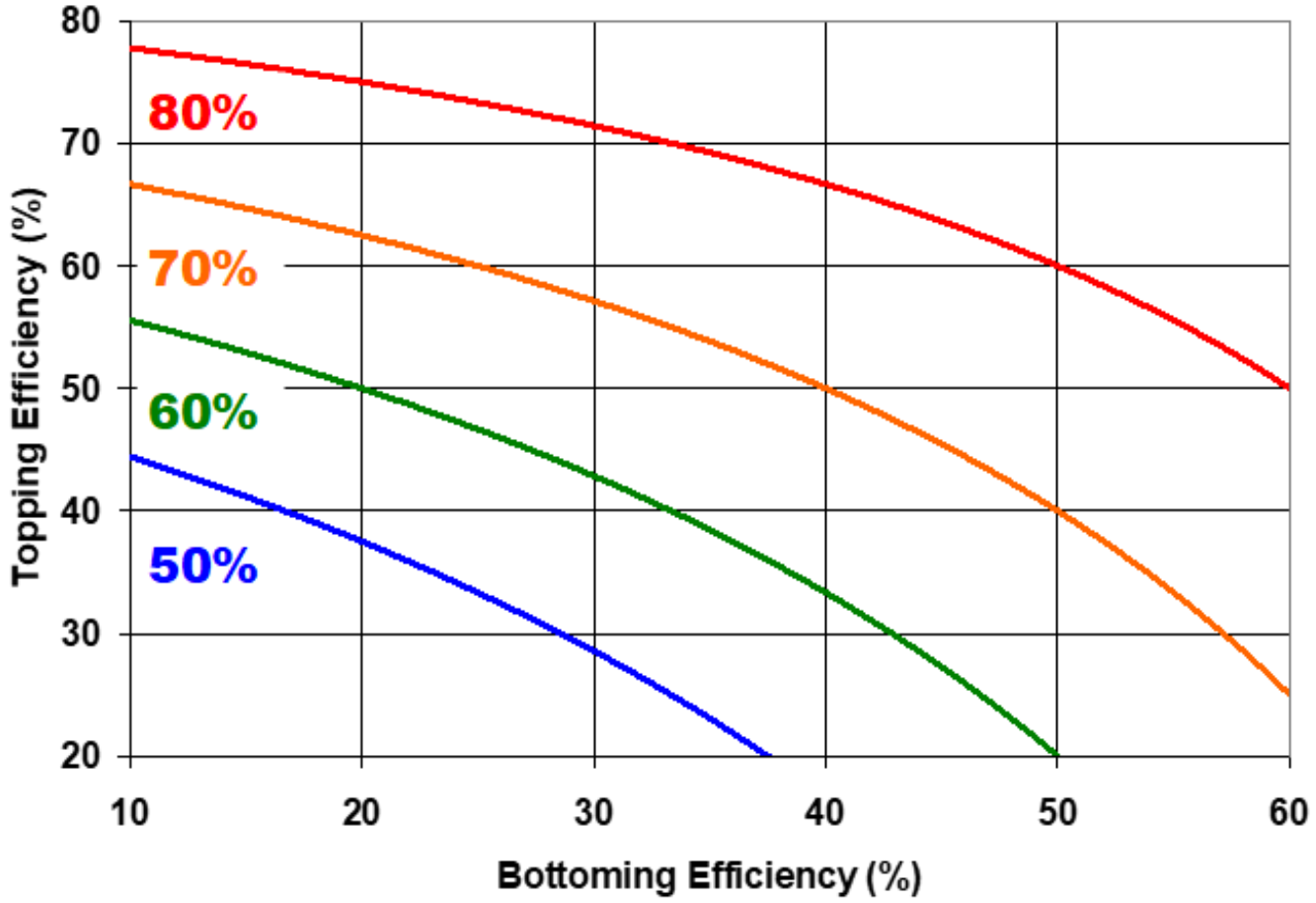
ICE Inlet Fuel Cooling $\dot{m}\int_{T_R}^{T} C_p dT$

FC Electric Power

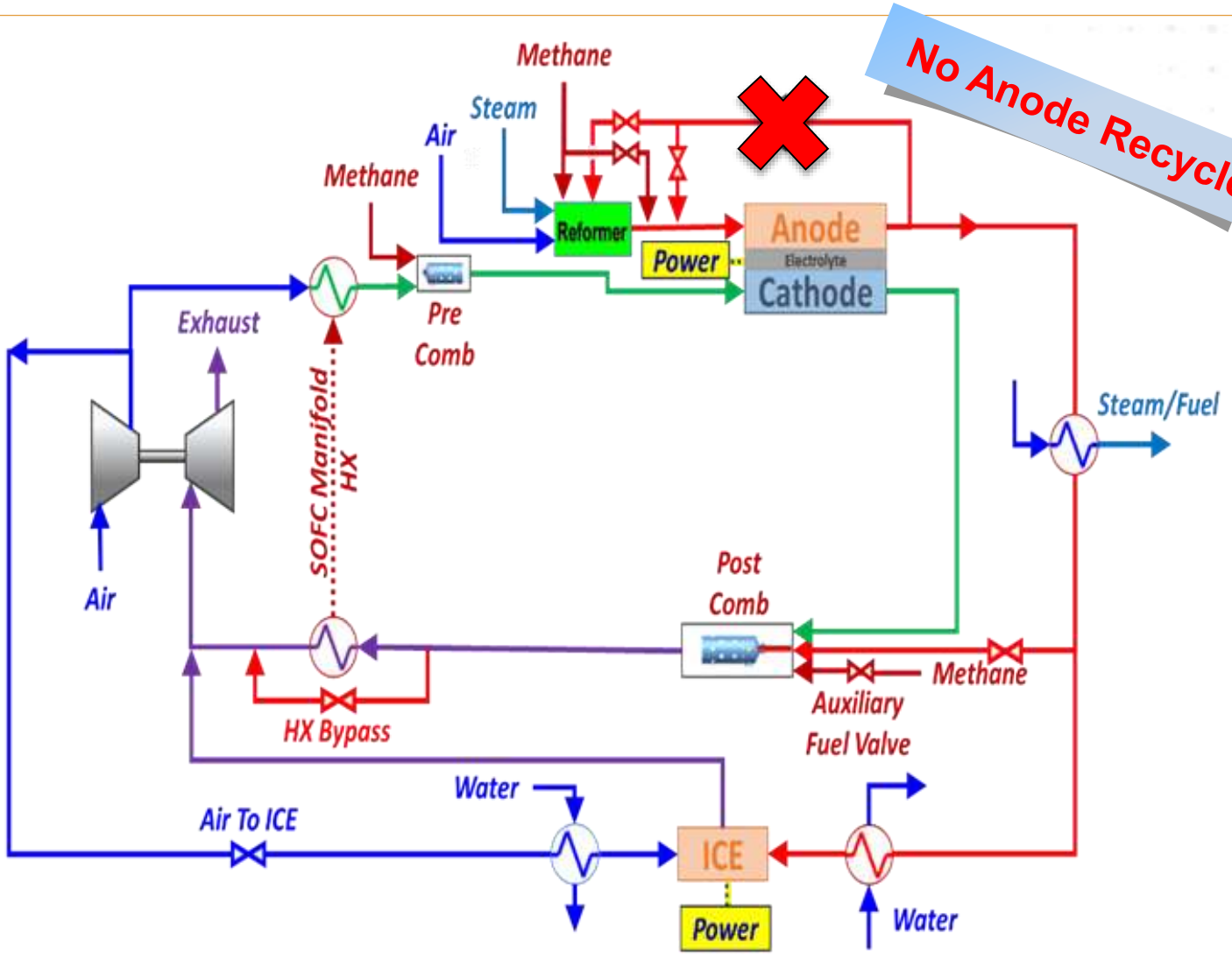
ICE Electric Power

FC/ICE Hybrid Cycle Evaluation

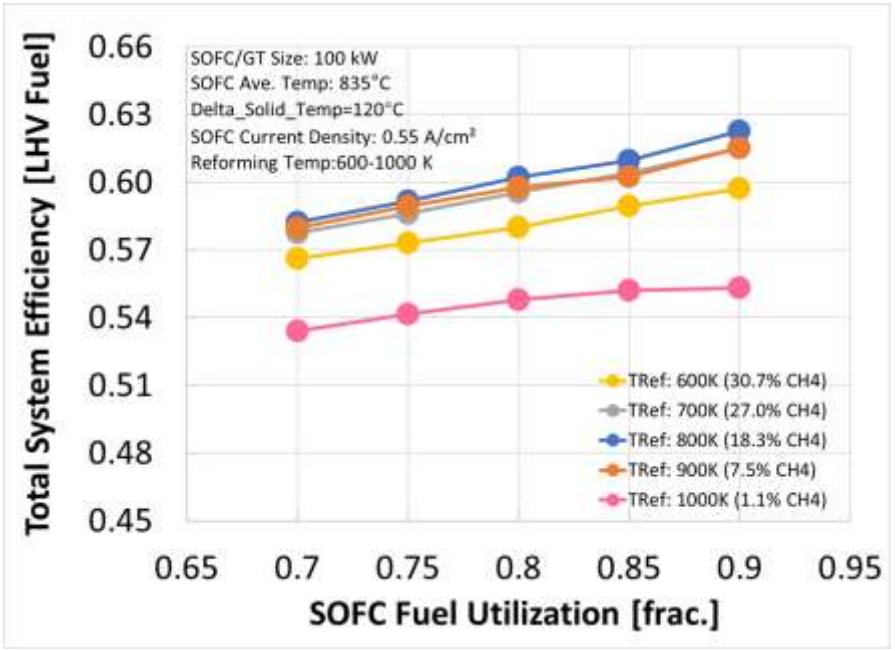
Topping and Bottoming Cycle

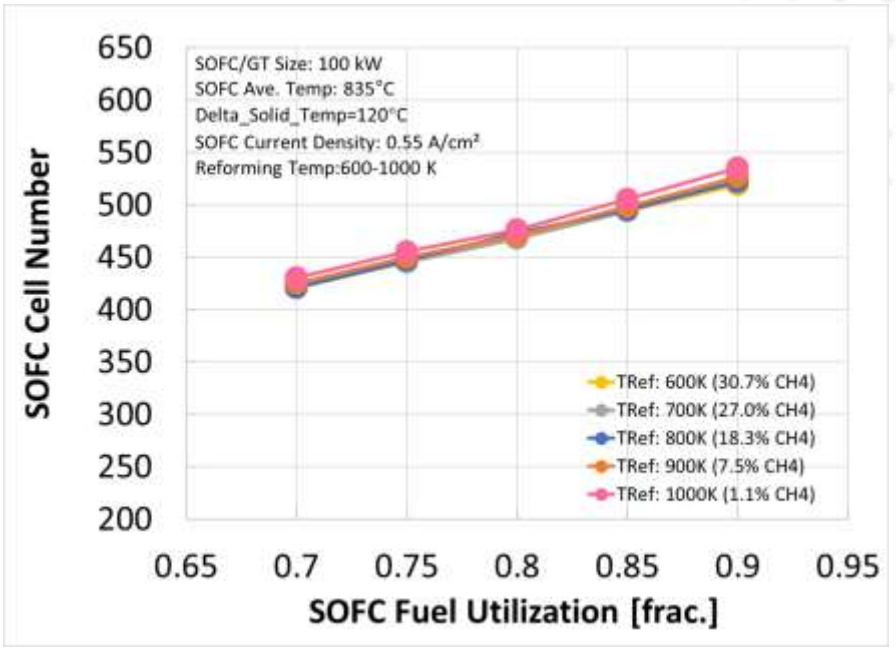


FC/ICE Cycle: Basic Configuration, No Anode Recycle



FC/ICE Cycle: Basic Configuration, No Anode Recycle



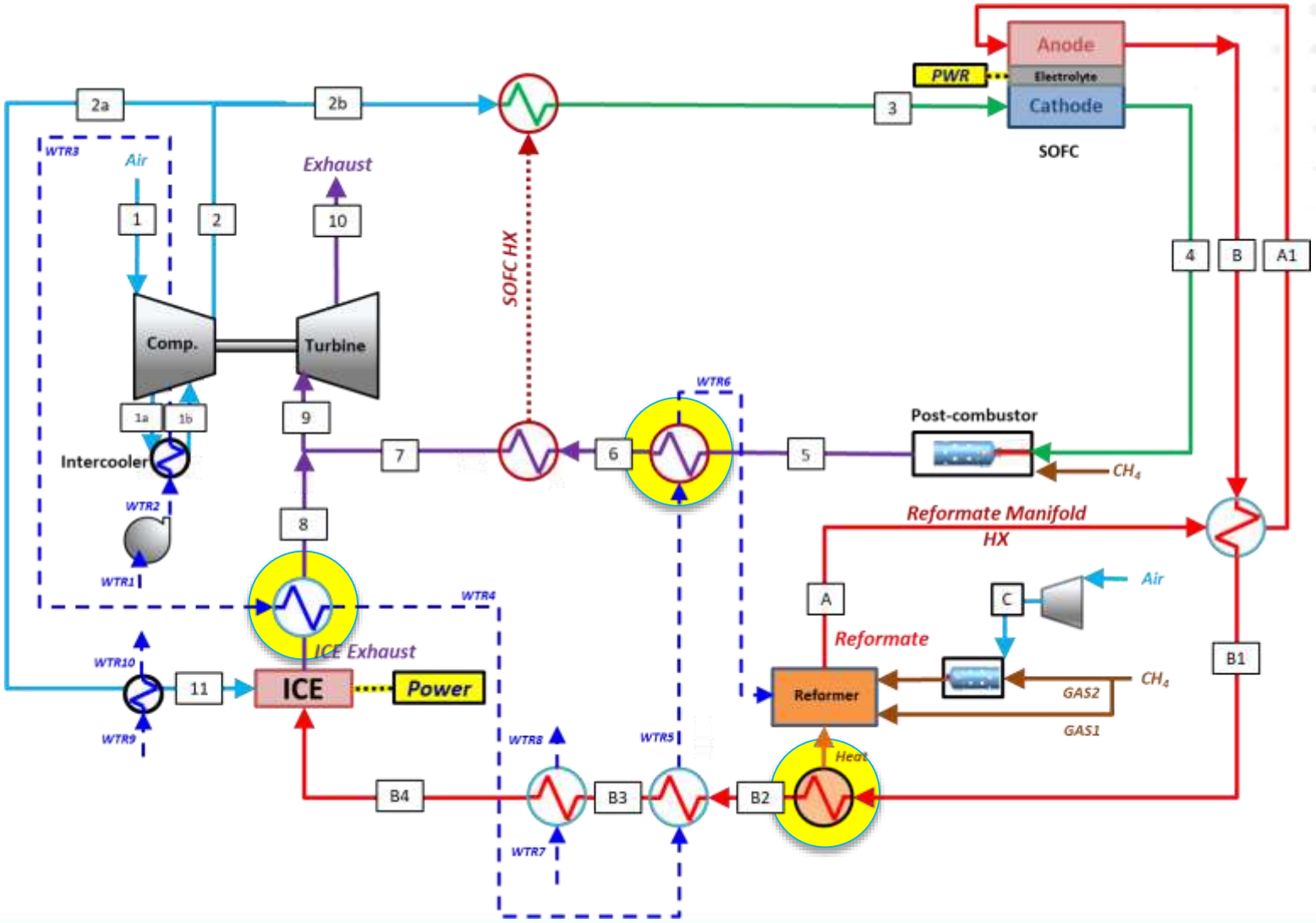


Hybrid System Efficiency and Stack Size as a Function of SOFC Fuel Utilization and Reformer Operating Temperature

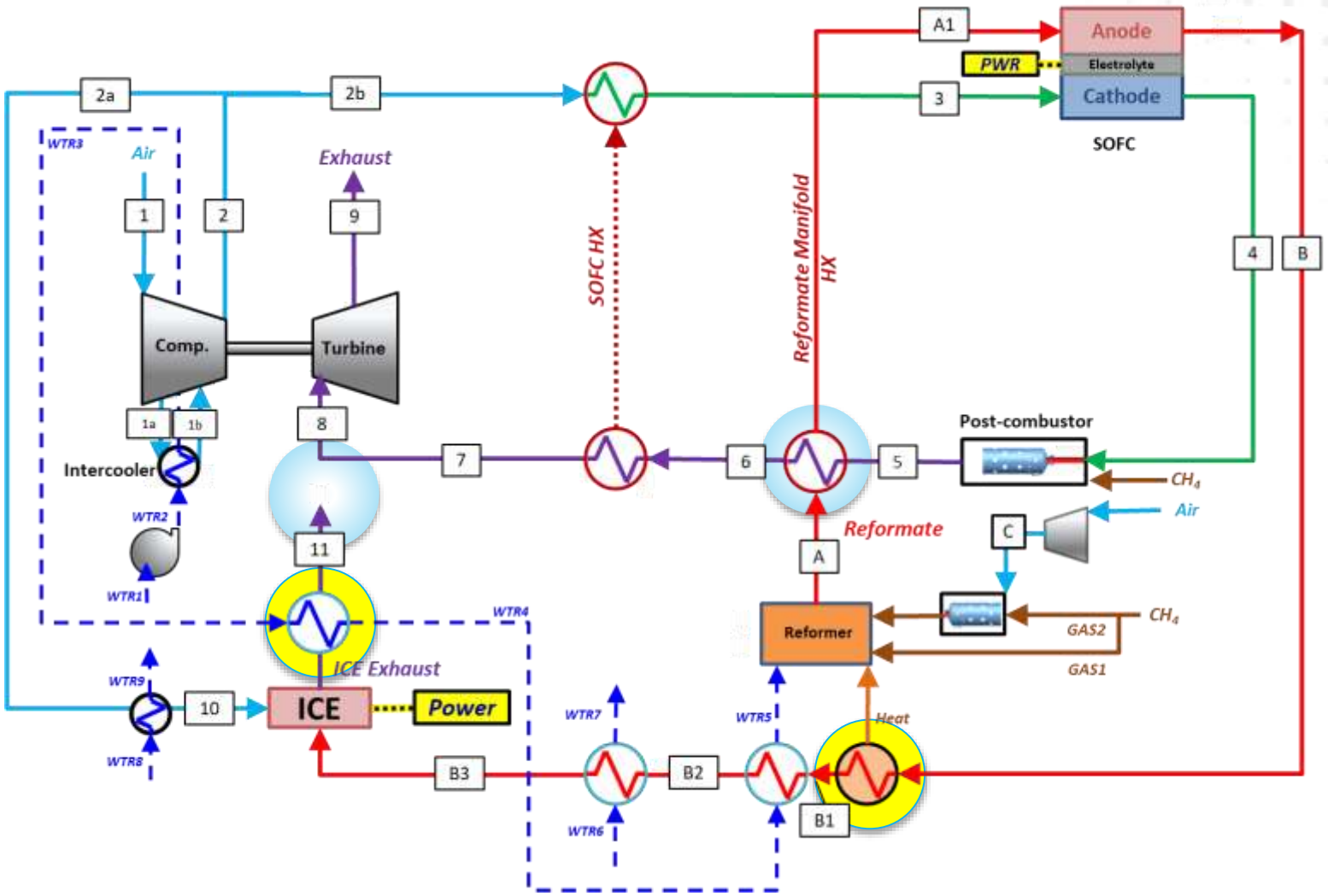
FC/ICE Cycle: Hybrid Cycle Evaluation

SOFC/ICE Configurations	Autothermal Ref.	Reformer at the Anode Exhaust		
Anode Exhaust Cooling	**ICE-1**	**ICE-2a**	**ICE-2b**	**ICE-2c**
Preheating CH_4 to reformer	✓	---	---	---
Steam to reformer	✓	✓	✓	✓
Add. cooling water	✓	✓	✓	✓
Reformer	---	✓	✓	✓
Preheating reformate to anode	---	✓	---	---
Turbine Inlet	**ICE-1**	**ICE-2a**	**ICE-2b**	**ICE-2c**
ICE exhaust + Turbine inlet ?	✓	✓	-	-
Reformer Steam Generation	**ICE-1**	**ICE-2a**	**ICE-2b**	**ICE-2c**
Intercooler	---	✓	✓	✓
Turbine exhaust	---	---	---	✓
ICE exhaust	---	✓	✓	✓
Anode exhaust	✓	✓	✓	✓
Cathode exhaust	---	✓	---	---
Cathode Exhaust	**ICE-1**	**ICE-2a**	**ICE-2b**	**ICE-2c**
Preheating reformate to anode	✓	---	✓	✓
Preheating cathode inlet air	✓	✓	✓	✓
Steam to reformer	---	✓	---	---

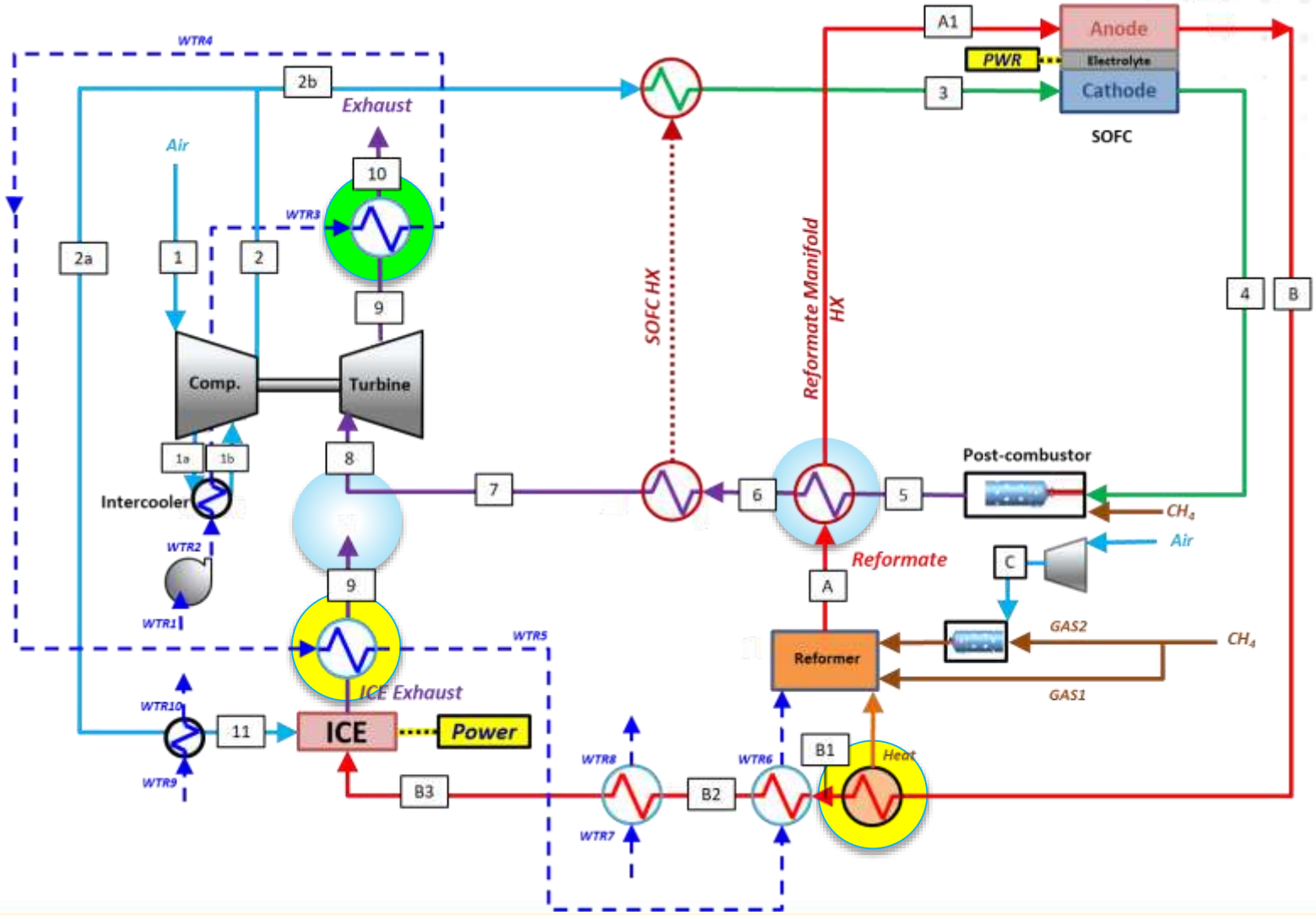
FC/ICE Cycle: Comparison, ICE Cycle-2a



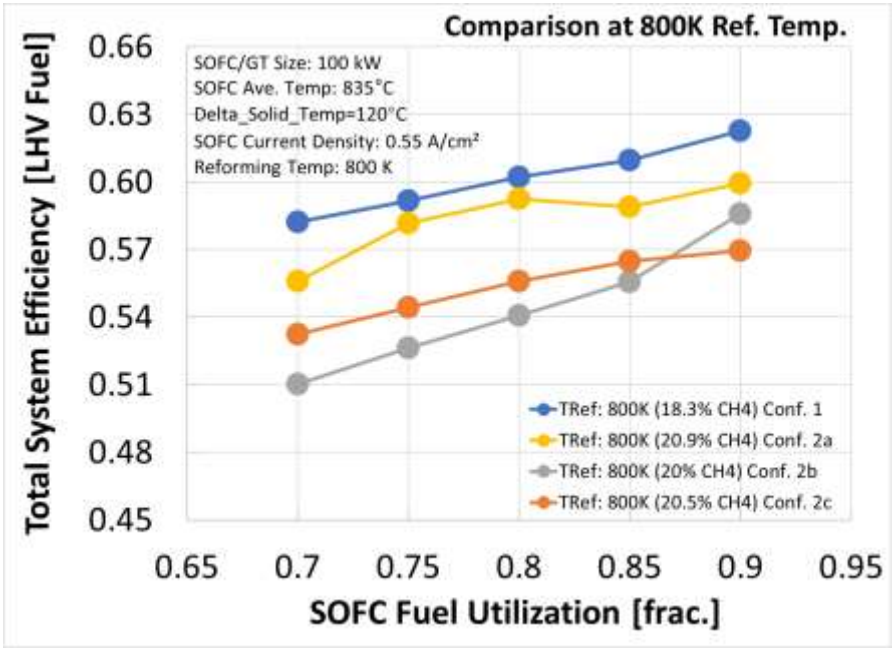
FC/ICE Cycle: Comparison, ICE Cycle-2b

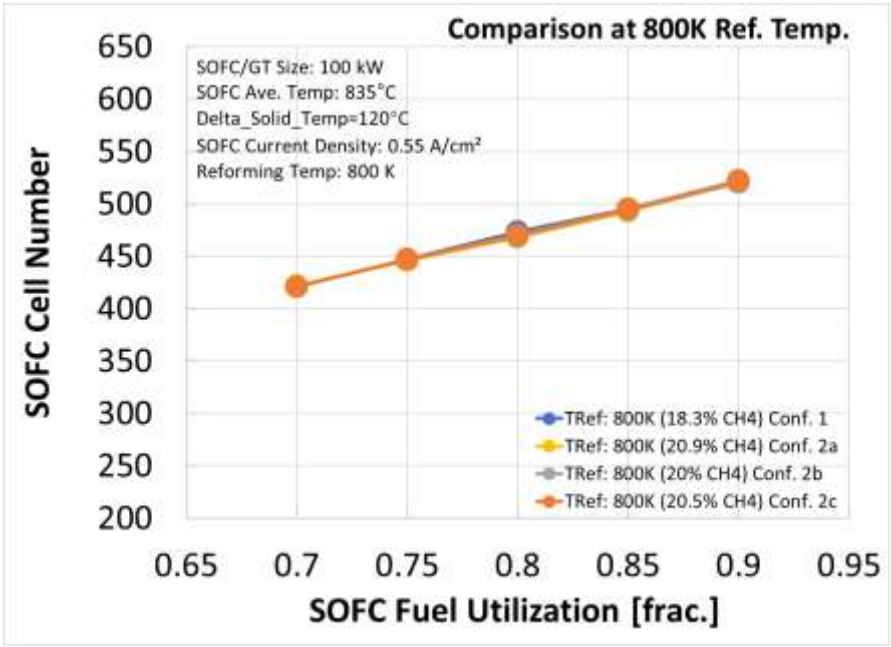


FC/ICE Cycle: Comparison, ICE Cycle-2c



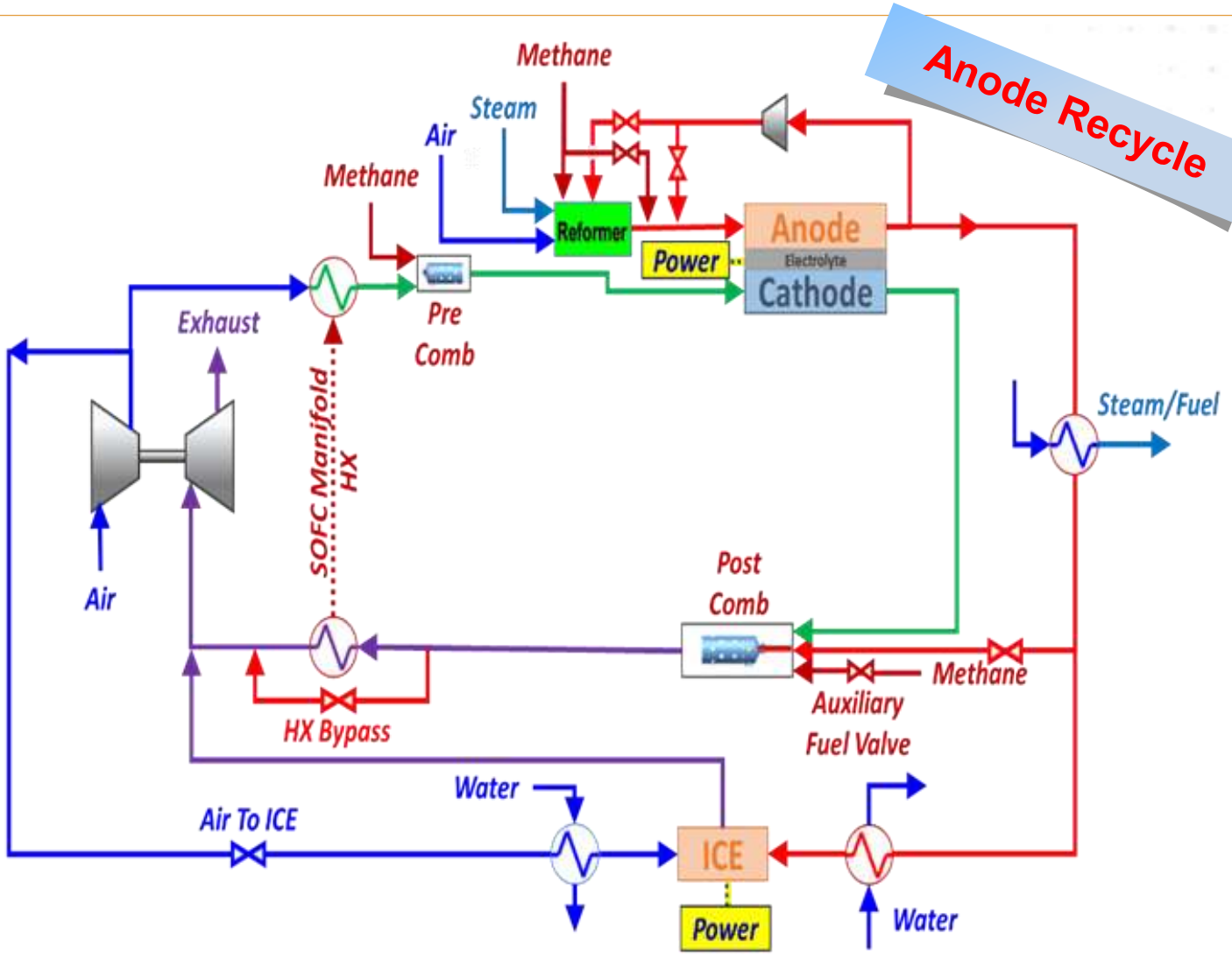
FC/ICE Cycle: Hybrid Cycle Evaluation (4 Cycles)



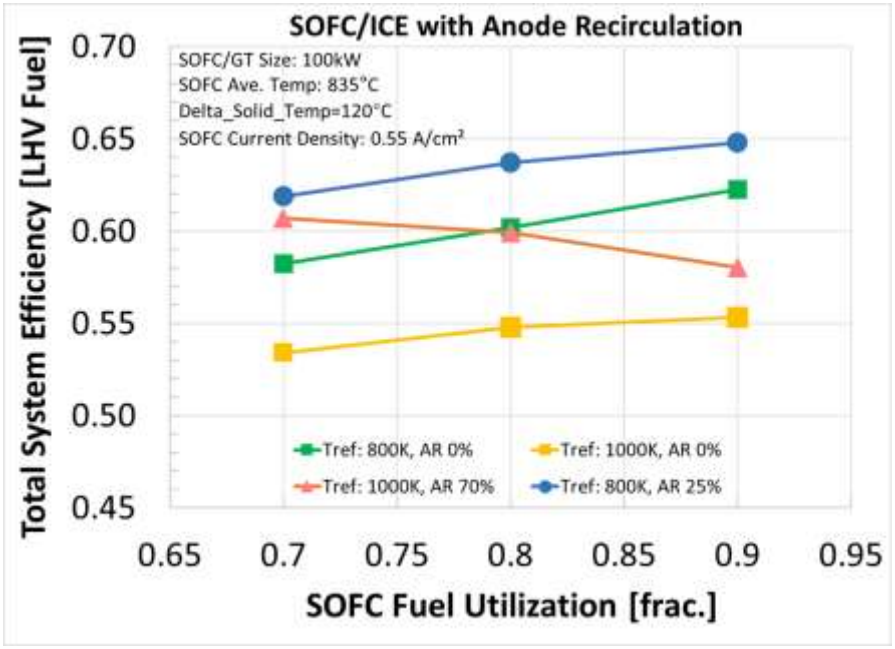


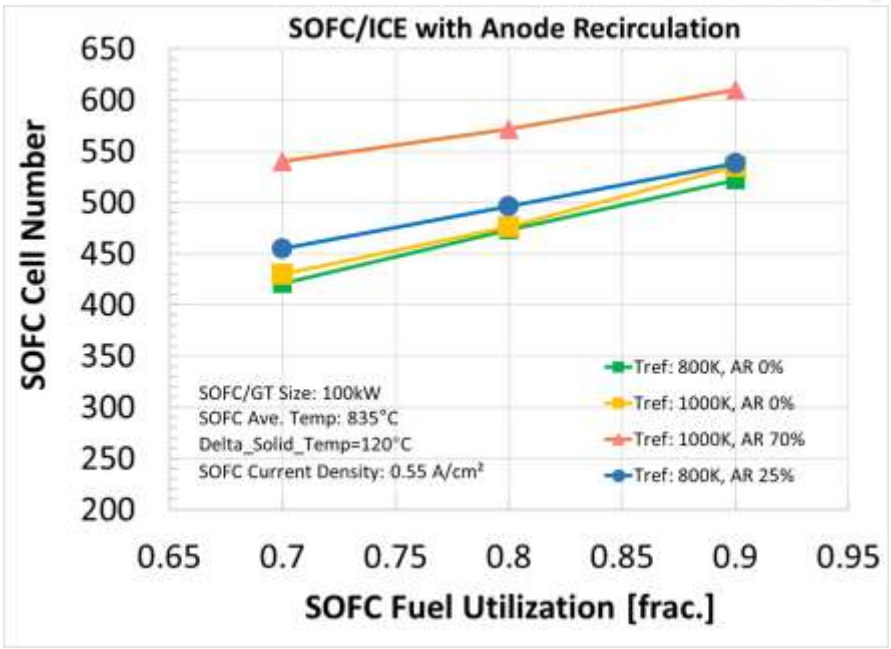
Hybrid System Efficiency and Stack Size as a Function of SOFC Fuel Utilization and Reformer Operating Temperature

FC/ICE Cycle: Basic Configuration, With Anode Recycle



FC/ICE Cycle: Basic Configuration, With Anode Recycle

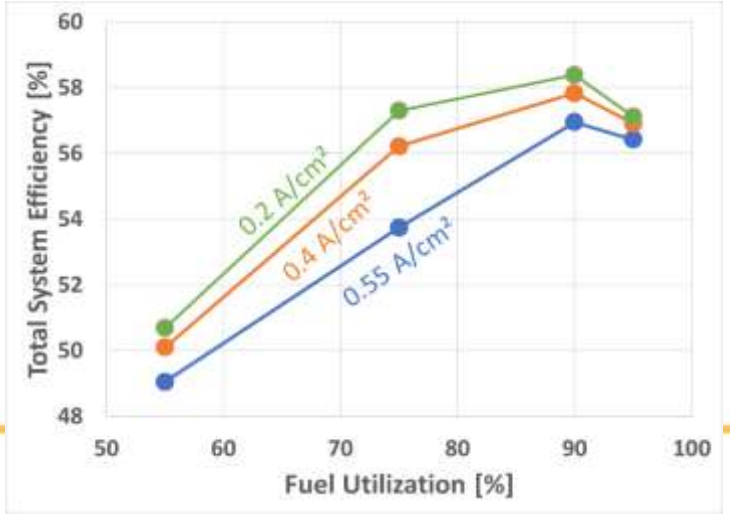




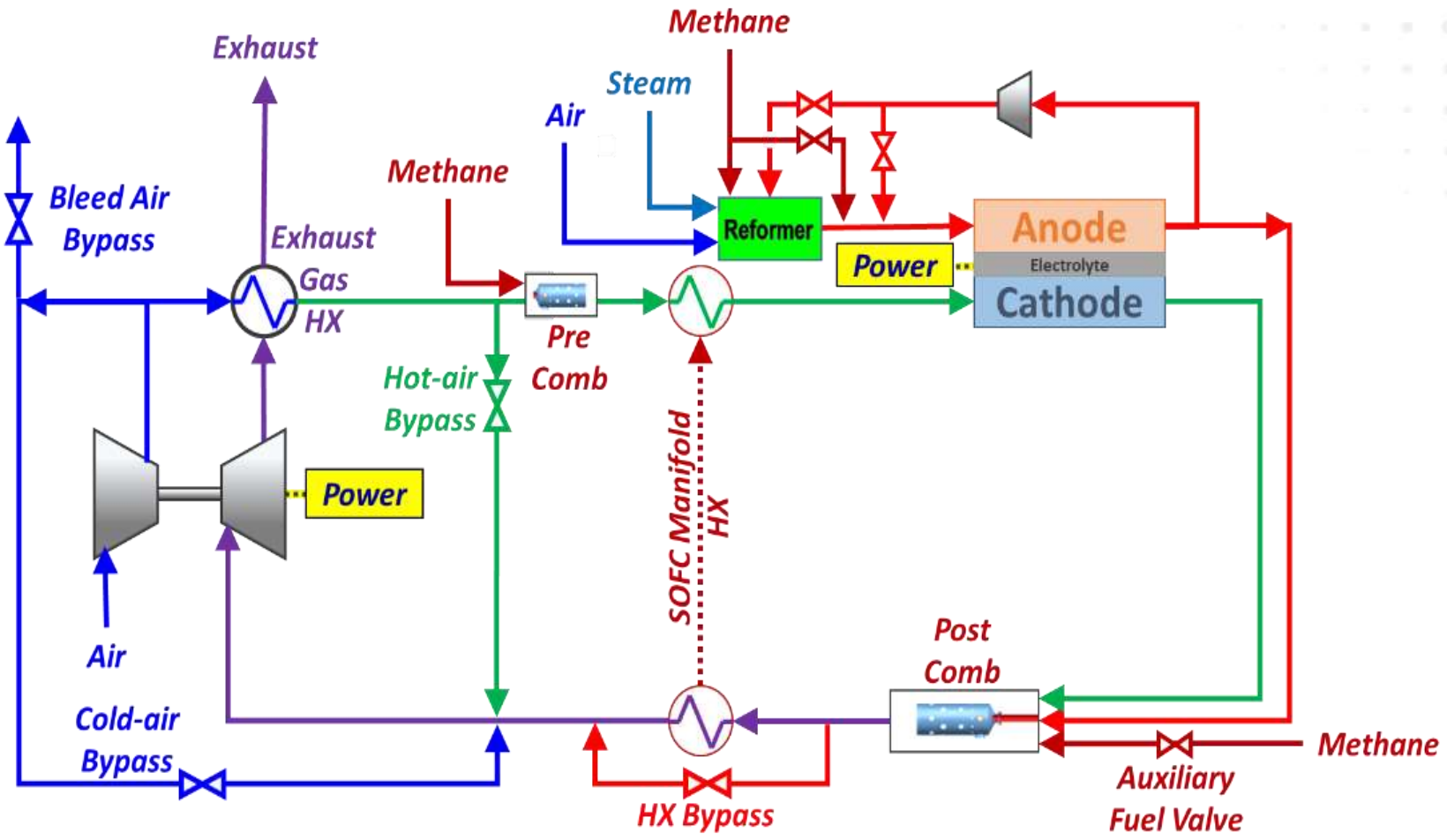
Hybrid System Efficiency and Stack Size in SOFC/ICE Cycle as a Function of SOFC Fuel Utilization and Anode Recycle Rate to Reformer at 800K and 1000K Reforming Temperature

FC/ICE Cycle: Summary

- Behaves as a Bottoming Cycle
- Thermal Integration have small affects on system efficiency
- High fuel utilization operation is needed to achieve high efficiency.
- Anode Recycle increases efficiency. May be the key to achieve 70% efficient cycle.



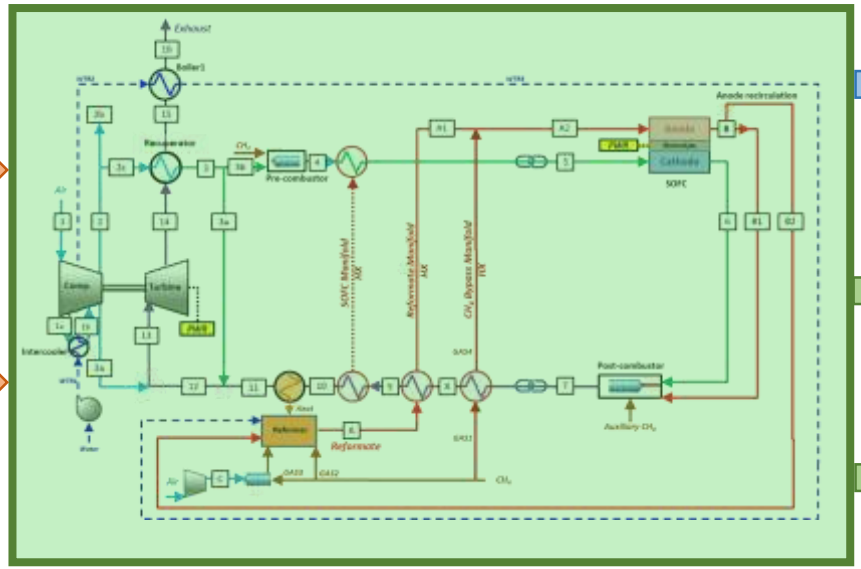
FC/GT Hybrid Cycle Evaluation



FC/GT Hybrid Cycle Evaluation

LHV-FC Fuel

LHV-C1 Fuel



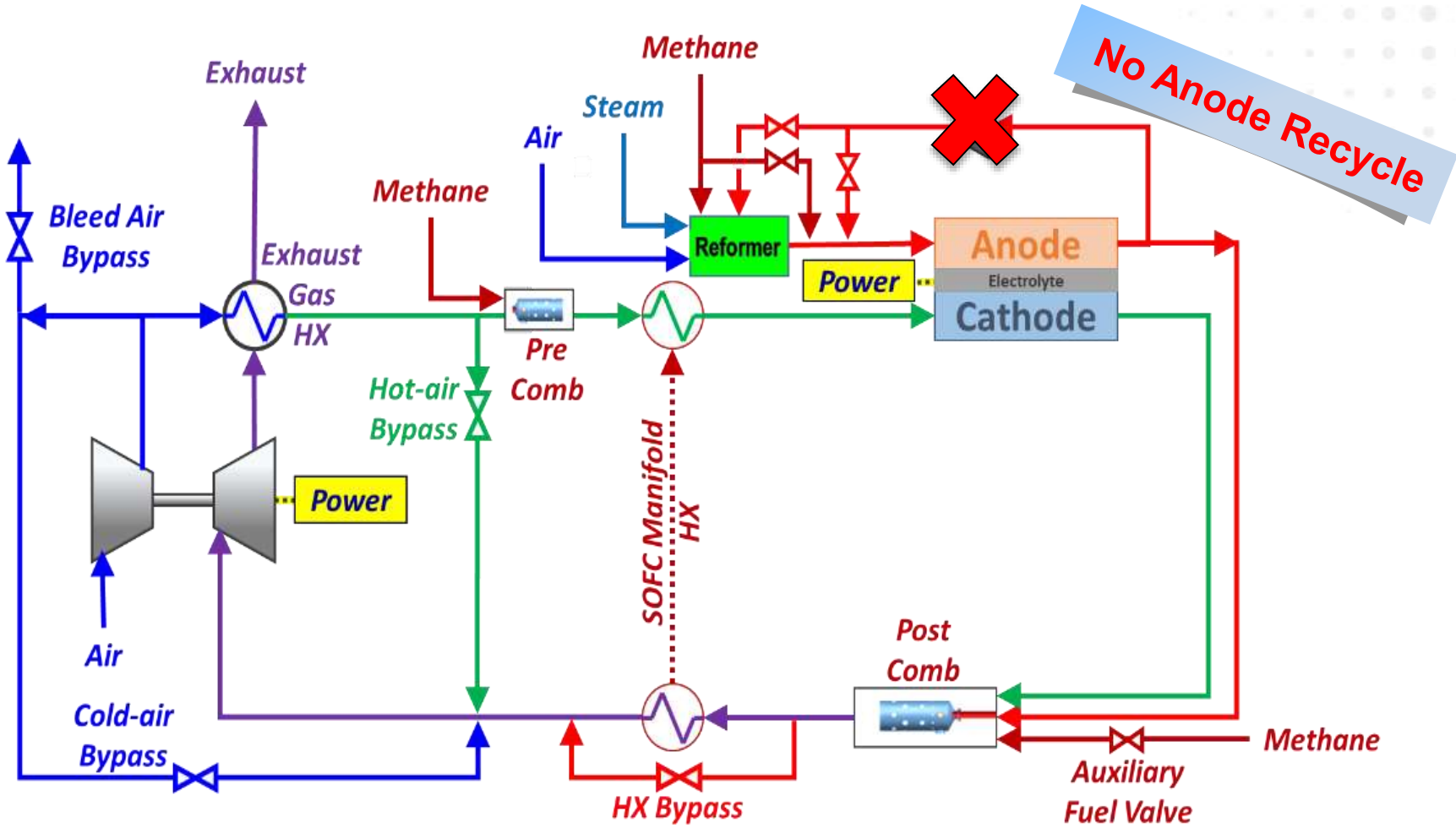
Recuperator Exhaust

$$\dot{m}\int_{T_R}^{T} C_p dT$$

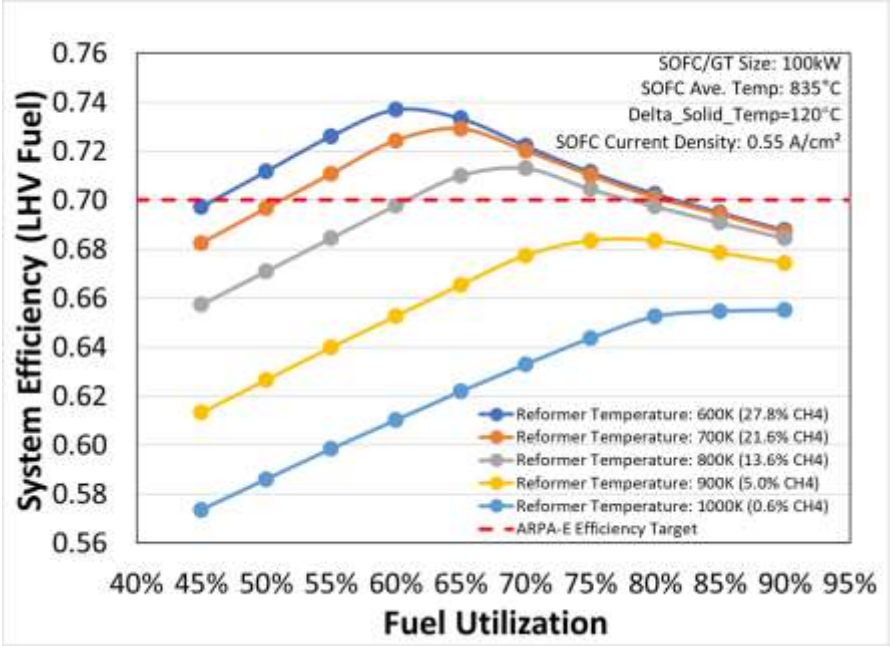
FC Electric Power

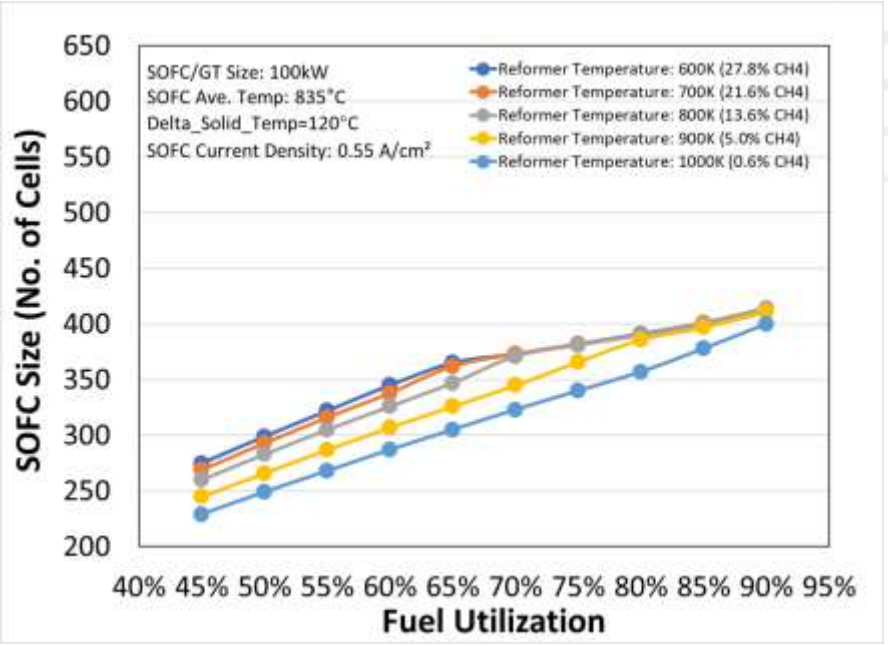
GT Electric Power

FC/GT Cycle: Autothermal Reformer, No Anode Recycle



FC/GT Cycle: Autothermal Reformer, No Anode Recycle



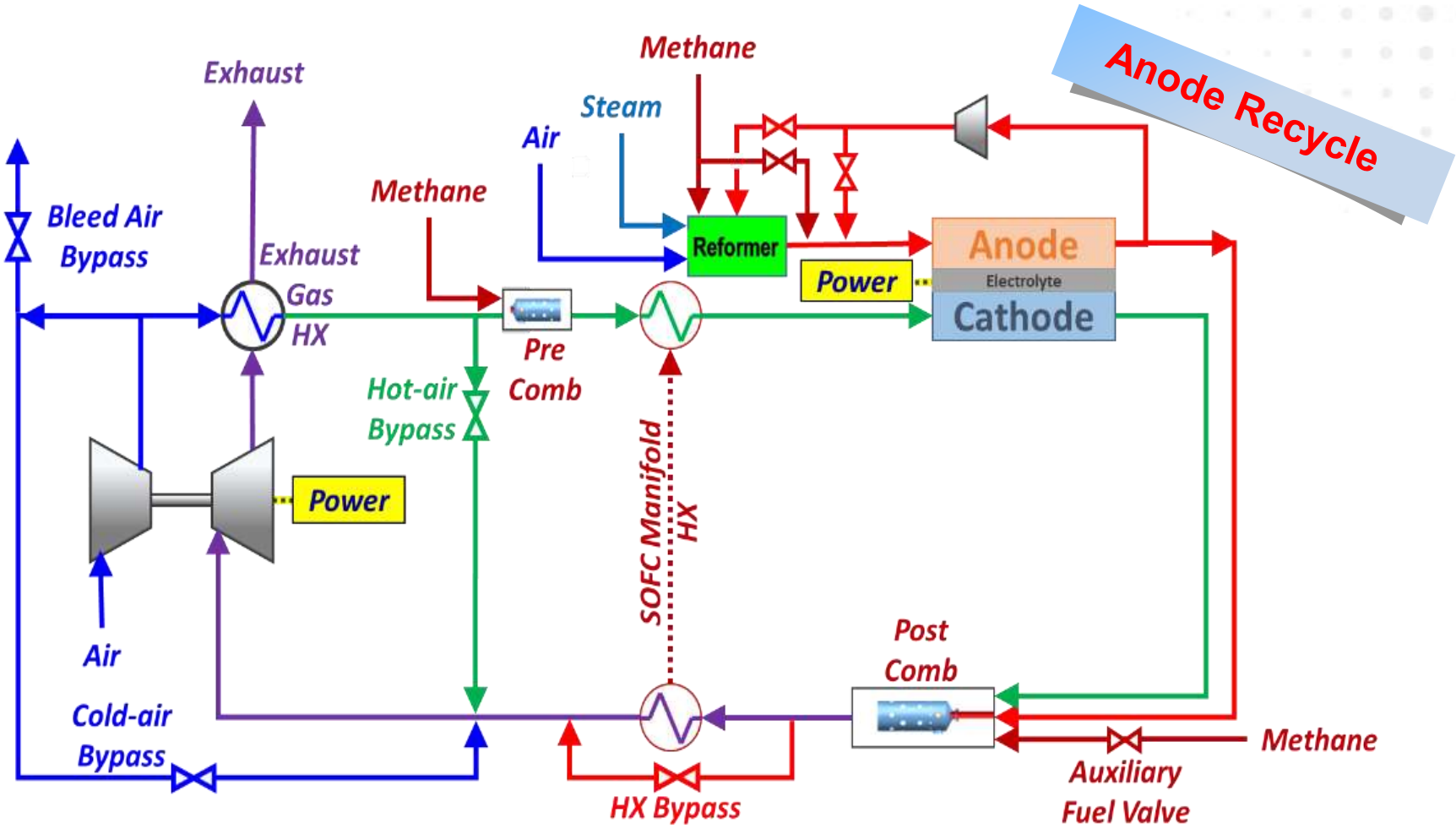


Hybrid System Efficiency and Stack Size as a Function of SOFC Fuel Utilization and Reformer Operating Temperature

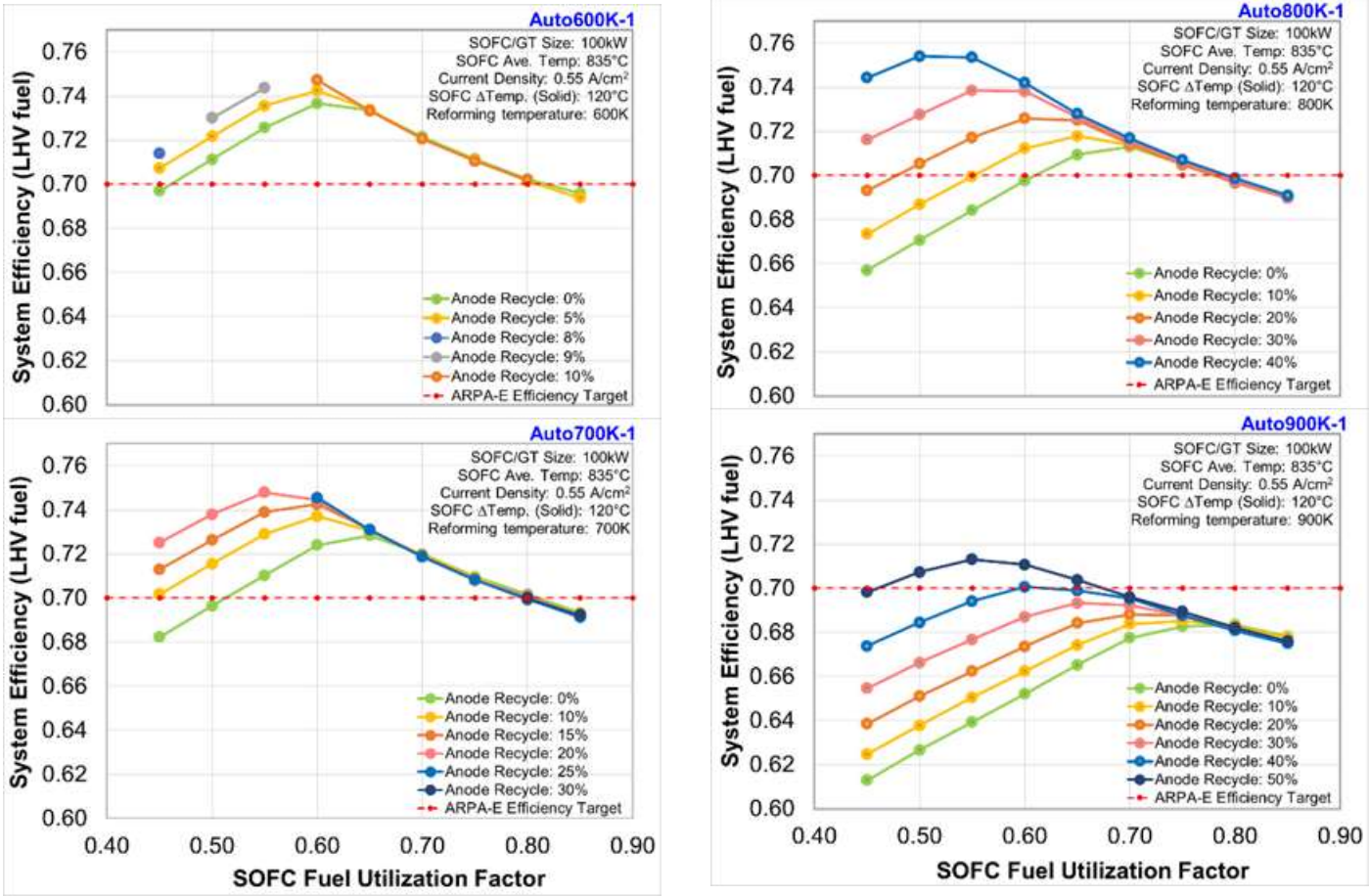
FC/GT Cycle: Autothermal Reformer, No Anode Recycle

U_f	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
70% Efficiency Target		600K	600K	600K	600K	600K	600K	600K		
			700K	700K	700K	700K	700K	700K		
					800K	800K	800K			
dT/dx (<10°C/cm)										
					700K					
			800K	800K	800K					
	900K	900K	900K	900K	900K	900K	900K			
	1000K	1000K	1000K	1000K	1000K	1000K	1000K			
$\|T_{solid} - T_{gas}\|$ (< 80°C)							600K	600K	600K	600K
					700K	700K	700K	700K	700K	700K
			800K	800K	800K	800K	800K	800K	800K	800K
	900K	900K	900K	900K	900K	900K	900K	900K	900K	900K
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K		
C_{IT} (< 850°C)							600K	600K	600K	600K
					700K	700K	700K	700K	700K	700K
			800K	800K	800K	800K	800K	800K	800K	800K
	900K	900K	900K	900K	900K	900K	900K	900K	900K	900K
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K
T_{IT} (<1300°C)				600K	600K	600K	600K	600K	600K	600K
			700K	700K	700K	700K	700K	700K	700K	700K
	800K	800K	800K	800K	800K	800K	800K	800K	800K	800K
	900K	900K	900K	900K	900K	900K	900K	900K	900K	900K
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K
PreC				NA	600K	600K	600K	600K	600K	600K
					NA	700K	700K	700K	700K	700K
					NA	NA	800K	800K	800K	800K
							NA	900K	900K	900K
HA	600K	600K	600K	NA						
	700K	700K	700K	700K	NA					
	800K	800K	800K	800K	NA	NA				
	900K	900K	900K	900K	900K	900K	NA			
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	NA	NA	NA

FC/GT Cycle: Autothermal Reformer, With Anode Recycle

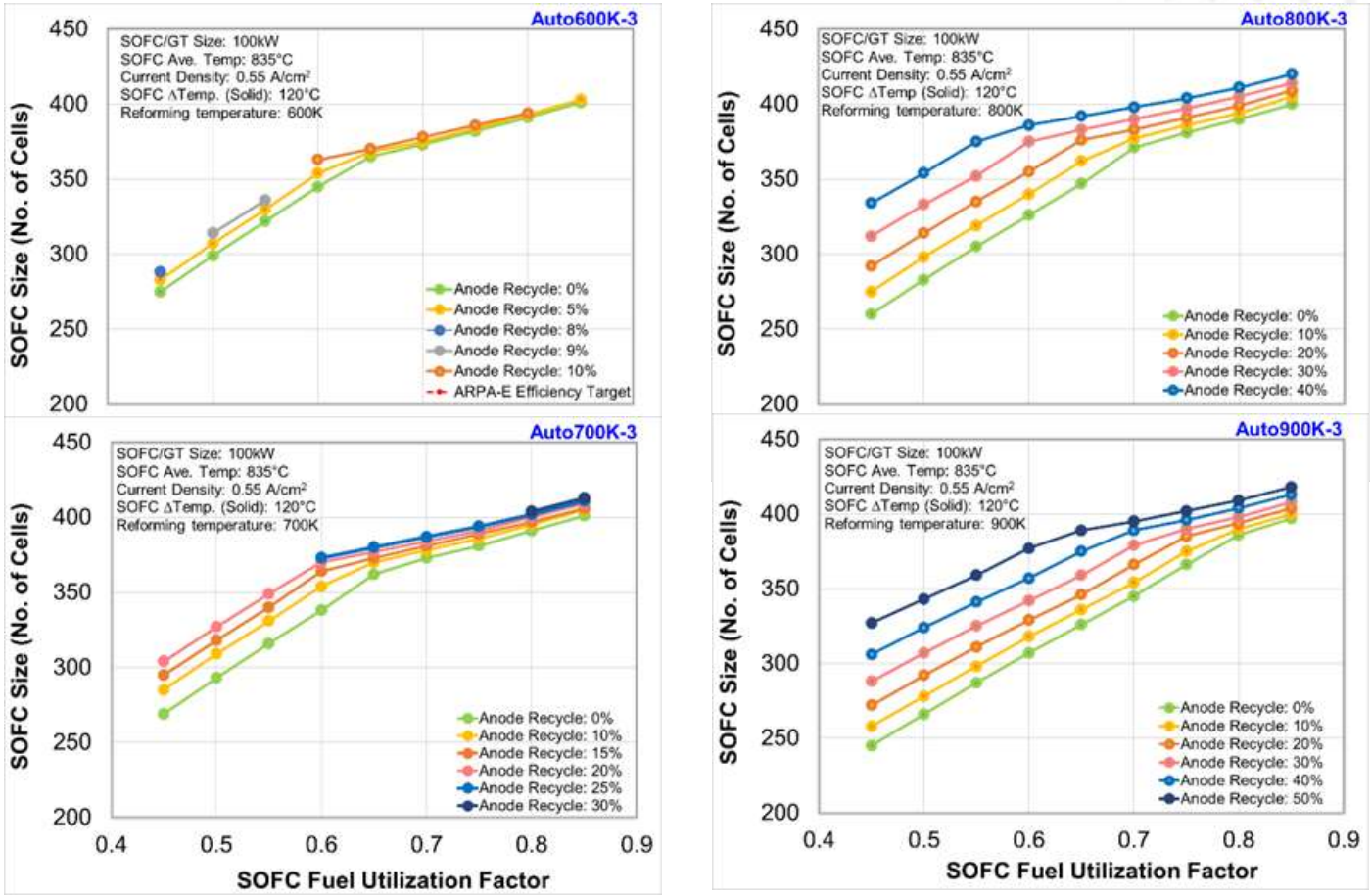


FC/GT Cycle: Autothermal Reformer, With Anode Recycle



Hybrid System Efficiency in SOFC/GT Cycle as a Function of Anode Recycle Rate to Reformer, SOFC Fuel Utilization and Reformer Operating Temperature

FC/GT Cycle: Autothermal Reformer, With Anode Recycle



SOFC Stack Size in SOFC/GT Cycle as a Function of Anode Recycle Rate to Reformer, SOFC Fuel Utilization and Reformer Operating Temperature

FC/GT Cycle: Autothermal Reformer, With Anode Recycle

U_f	45%	50%	55%	60%	65%	70%	75%	80%	85%
70% Efficiency Target	600K (5, 8%)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	
	700K (AR)	700K (AR)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	
	800K (30, 40%)	800K (20-40%)	800K (AR)	800K (AR)	800K (All)	800K (All)	800K (All)	800K (40%)	
		900K (50%)	900K (50%)	900K (50%)	900K (50%)				
dT/dx (<10°C/cm)					600K (10%)	600K (10%)			
			700K (25%)	700K (AR)	700K (AR)	700K (AR)			
		800K (40%)	800K (All)	800K (All)	800K (All)	800K (AR)	800K (30, 40%)		
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (40, 50%)	
$(T_{solid} - T_{gas})$ (< 80°C)						600K (All)	600K (All)	600K (All)	600K (All)
					700K (All)	700K (All)	700K (All)	700K (All)	700K (All)
		800K (40%)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)
C_{Π} (< 850°C)						600K (All)	600K (All)	600K (All)	600K (All)
					700K (All)	700K (All)	700K (All)	700K (All)	700K (All)
		800K (40%)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)
T_{Π} (<1300°C)			600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)
		700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)
	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)
STCR>2:1	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)	600K (All)
	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)
	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)

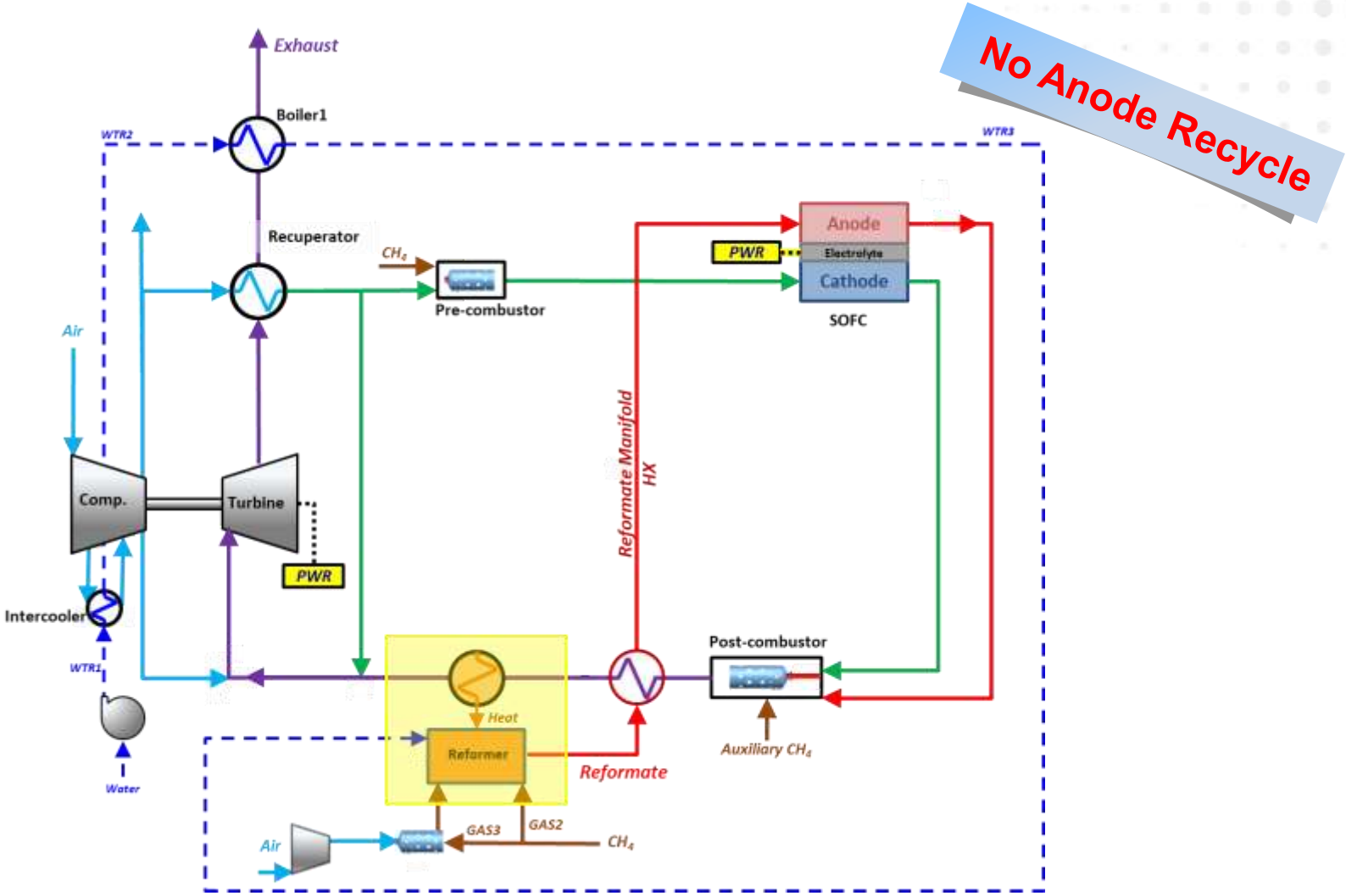
FC/GT Cycle: Autothermal Reformer

Anode Recycle Comparison

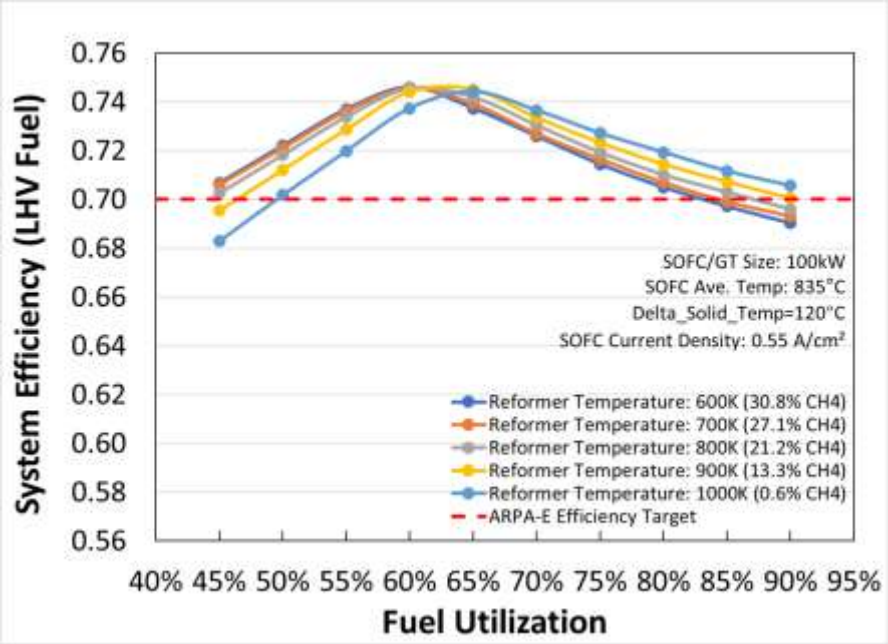
	0% Anode Recycle		With Anode Recycle		Comparison	
Reforming Temperature	**Max. System Efficiency**	**Fuel Utilization**	**Max. System Efficiency**	**Fuel Utilization**	**Efficiency Gain (% point)**	**Change in SOFC Size, (AR)**
600K	73.7%	60%	74.7%	60% (10%AR)	1.0%	5.2%
700K	72.9%	65%	74.8%	55% (20%AR)	1.9%	-3.6%
800K	71.3%	70%	75.4%	50% (40%AR)	4.1%	-4.6%
900K	68.4%	80%	71.3%	55% (50%AR)	2.9%	-7.0%

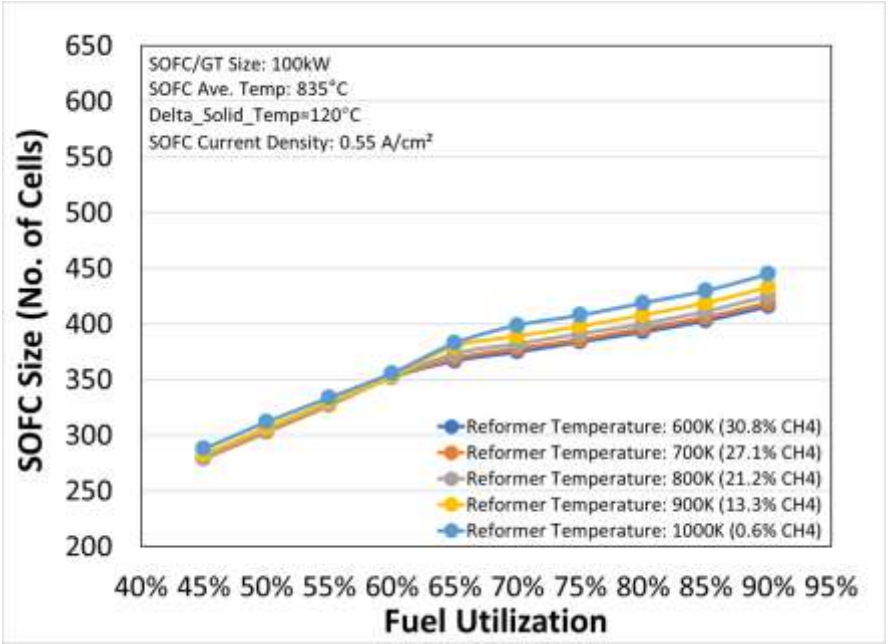
Comparison of Optimal Conditions in SOFC/GT Cycle with and without Anode recycle

FC/GT Cycle: Reformer at GT Inlet, No Anode Recycle



FC/GT Cycle: Reformer at GT Inlet, No Anode Recycle





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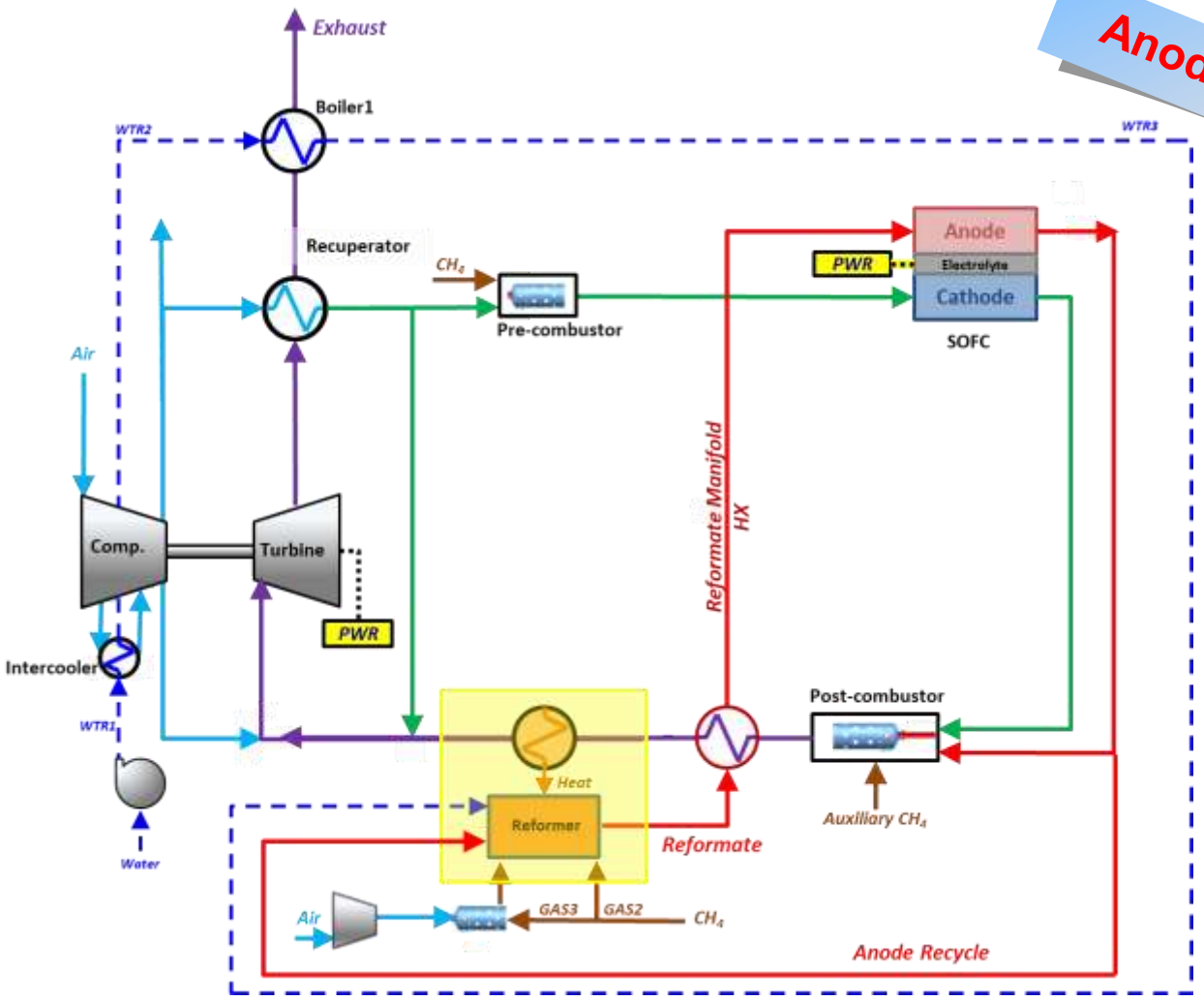
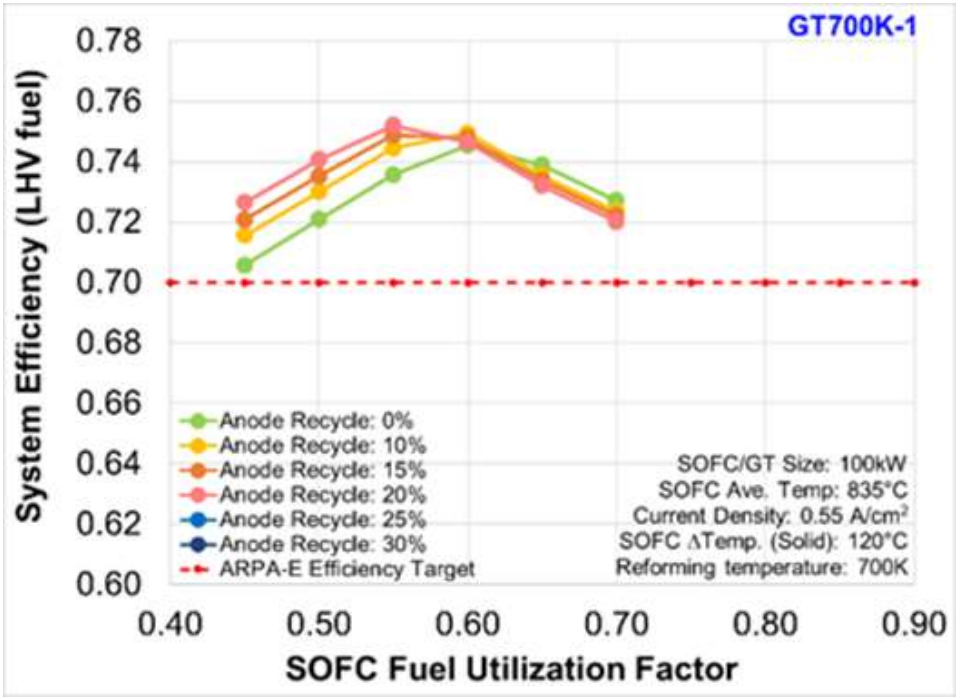
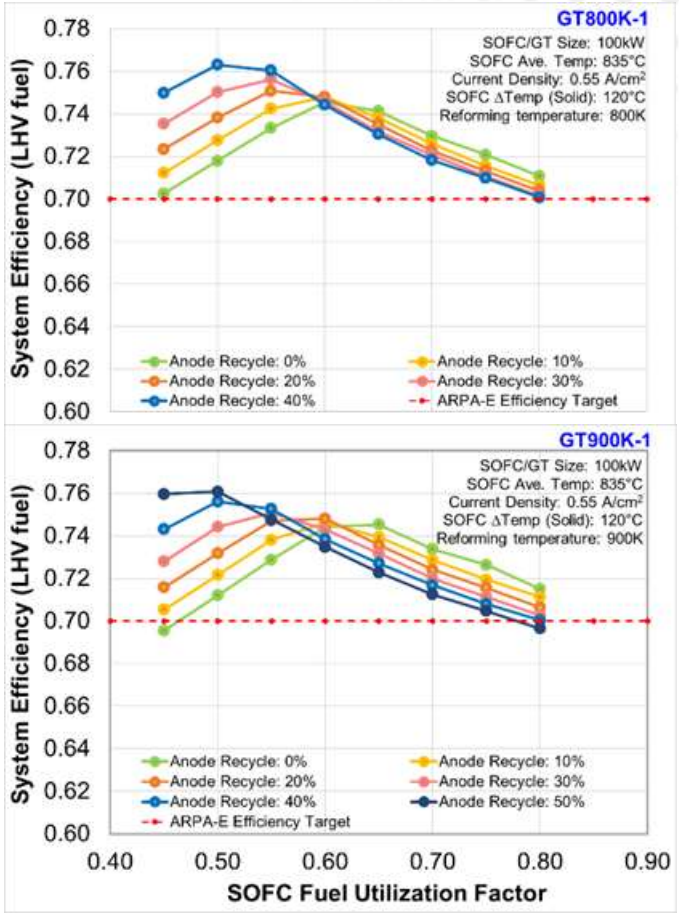
U_f	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
70% Efficiency Target	600K	600K	600K	600K	600K	600K	600K	600K		
	700K	700K	700K	700K	700K	700K	700K	700K		
	800K	800K	800K	800K	800K	800K	800K	800K	800K	
		900K	900K	900K	900K	900K	900K	900K	900K	900K
		1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K
dT/dx (<10°C/cm)										
			700K	700K						
			800K	800K	800K					
	900K	900K	900K	900K	900K					
	1000K	1000K	1000K	1000K	1000K	1000K	1000K			
$\lvert T_{solid} - T_{gas} \rvert$ (< 80°C)							600K	600K	600K	600K
						700K	700K	700K	700K	700K
				800K	800K	800K	800K	800K	800K	800K
	900K	900K	900K	900K	900K	900K	900K	900K	900K	900K
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K
C_{IT} (< 850°C)						600K	600K	600K	600K	600K
					700K	700K	700K	700K	700K	700K
				800K	800K	800K	800K	800K	800K	800K
	900K	900K	900K	900K	900K	900K	900K	900K	900K	900K
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K
T_{IT} (<1300°C)			600K	600K	600K	600K	600K	600K	600K	600K
			700K	700K	700K	700K	700K	700K	700K	700K
	800K	800K	800K	800K	800K	800K	800K	800K	800K	800K
	900K	900K	900K	900K	900K	900K	900K	900K	900K	900K
	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K	1000K

FC/GT Cycle: Reformer at GT Inlet, With Anode Recycle



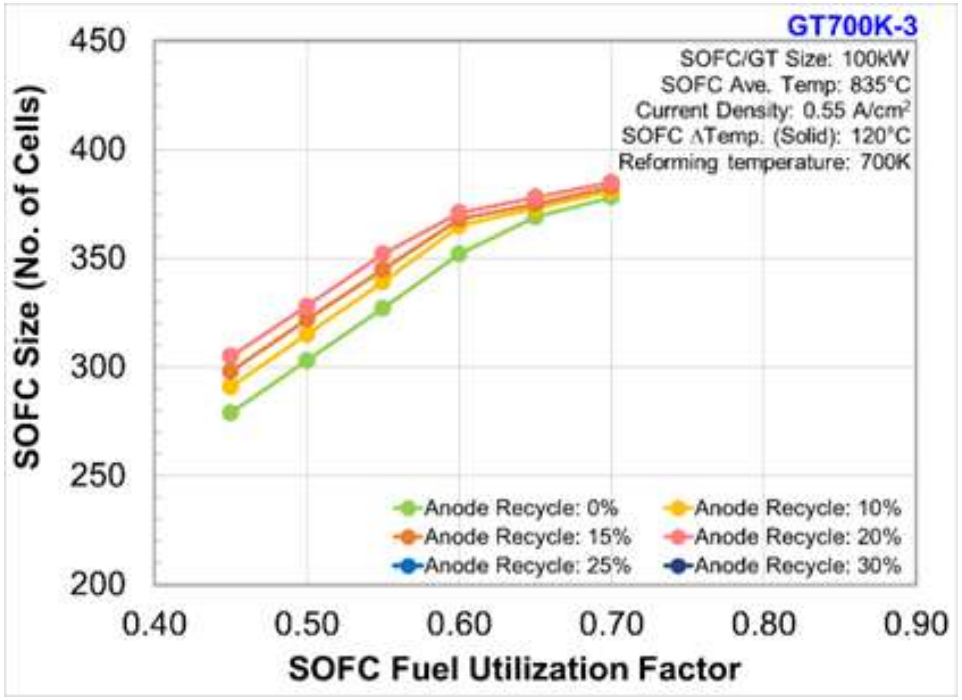
FC/GT Cycle: Reformer at GT Inlet, With Anode Recycle

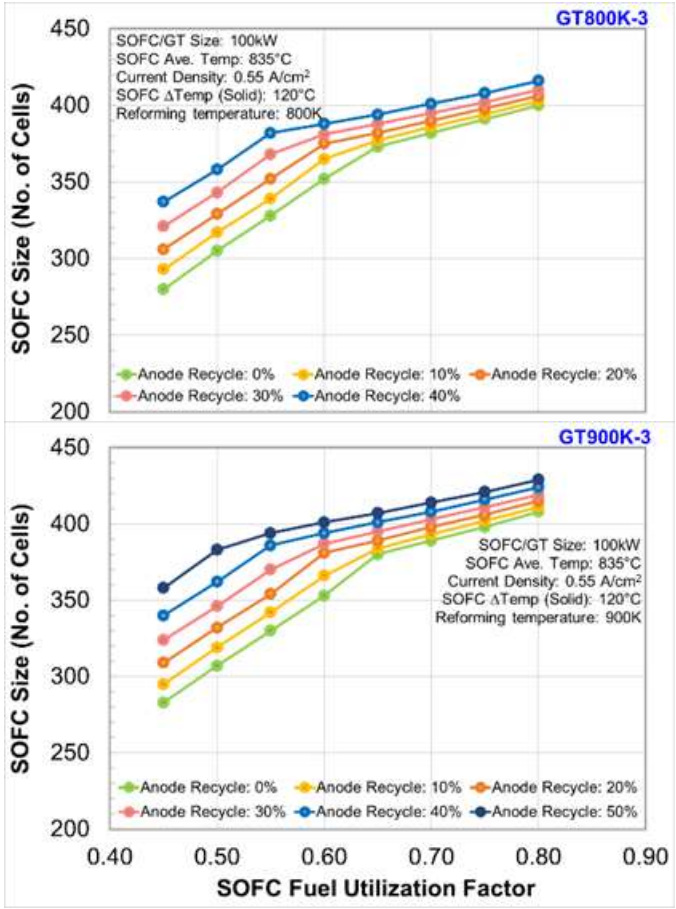




Hybrid System Efficiency in SOFC/GT Cycle as a Function of Anode Recycle Rate to Reformer, SOFC Fuel Utilization and Reformer Operating Temperature

FC/GT Cycle: Reformer at GT Inlet, With Anode Recycle





Stack Size in SOFC/GT Cycle as a Function of Anode Recycle Rate to Reformer, SOFC Fuel Utilization and Reformer Operating Temperature

FC/GT Cycle: Reformer at GT Inlet, With Anode Recycle

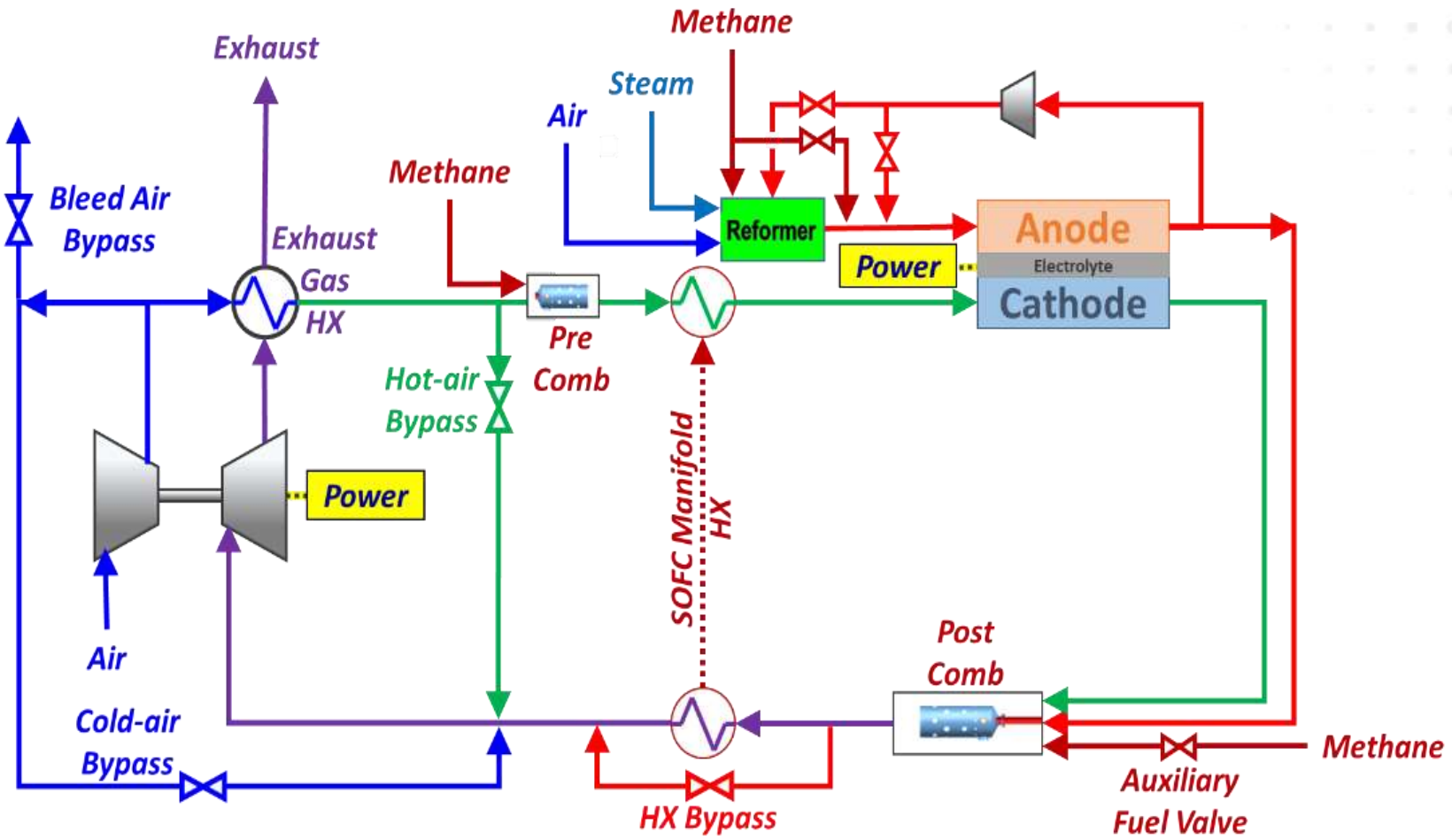
U_f	45%	50%	55%	60%	65%	70%	75%	80%
70% Efficiency Target	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	NA	NA
	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (AR)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	
dT/dx (<10°C/cm)			700K (All)	700K (All)	700K (All)	700K (15, 20%)	NA	NA
			800K (All)	800K (All)	800K (All)	800K (20-40%)	800K (40%)	
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (20, 30%)	900K (40, 50%)	
($T_{solid} - T_{gas}$) (< 80°C)						700K (All)	NA	NA
		800K (40%)	800K (30, 40%)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)
CIT (< 850°C)					700K (All)	700K (All)	NA	NA
			800K (20-40%)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)	900K (All)
TIT (<1300°C)				700K (AR)	700K (All)	700K (All)	NA	NA
			800K (40%)	800K (AR)	800K (All)	800K (All)	800K (All)	800K (All)
		900K (50%)	900K (30-50%)	900K (AR)	900K (All)	900K (All)	900K (All)	900K (All)
STCR>2:1	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	700K (All)	NA	NA
	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)	800K (All)
	900K (AR)	900K (AR)	900K (AR)	900K (AR)	900K (AR)	900K (AR)	900K (AR)	900K (AR)

FC/GT Cycle: Summary

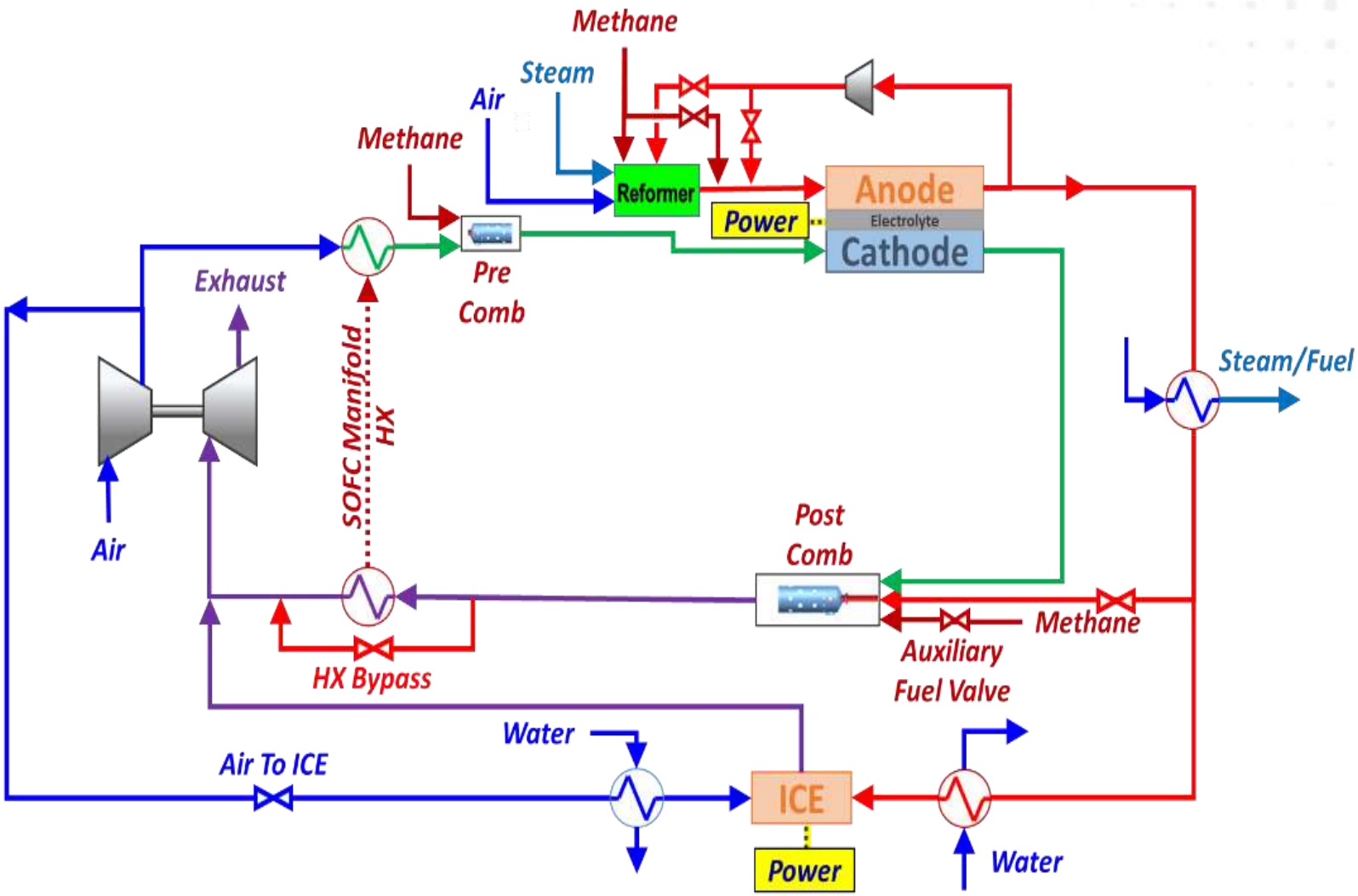
- Thermal Integration
  - Expands cycle capabilities
  - Enhances system flexibility
  - Obviates the need for Anode Recycle
  - Requires complicated control strategies

- On-anode reforming is not justified if thermal integration can be realized

FC/GT Cycle: Exploration of Potential Cycle Modifications



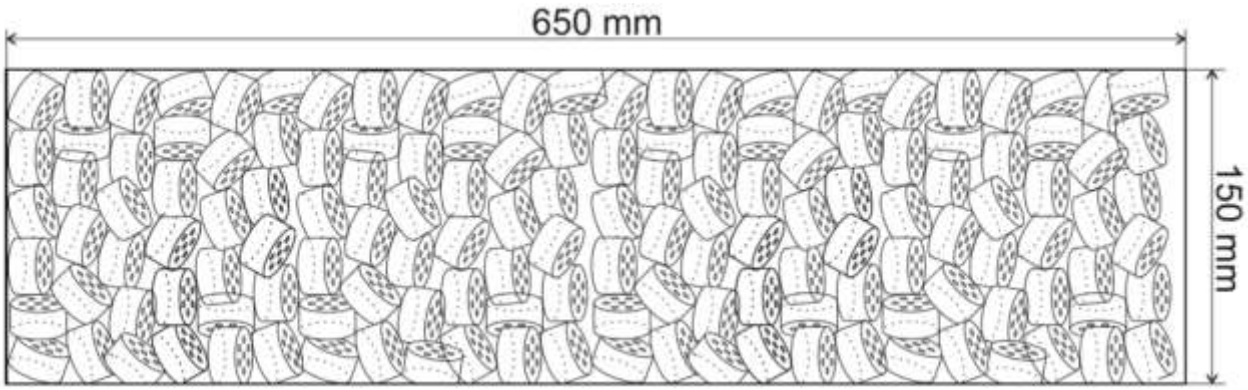
FC/ICE Cycle: Exploration of Potential Cycle Modifications

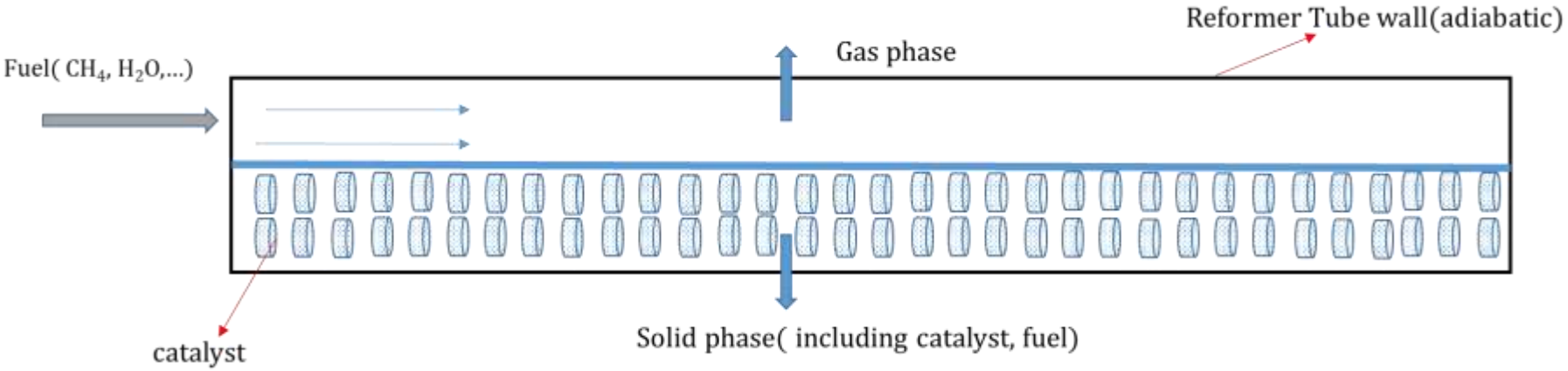


Real Time Reformer/Fuel Cell Model Reconfiguration

Completed

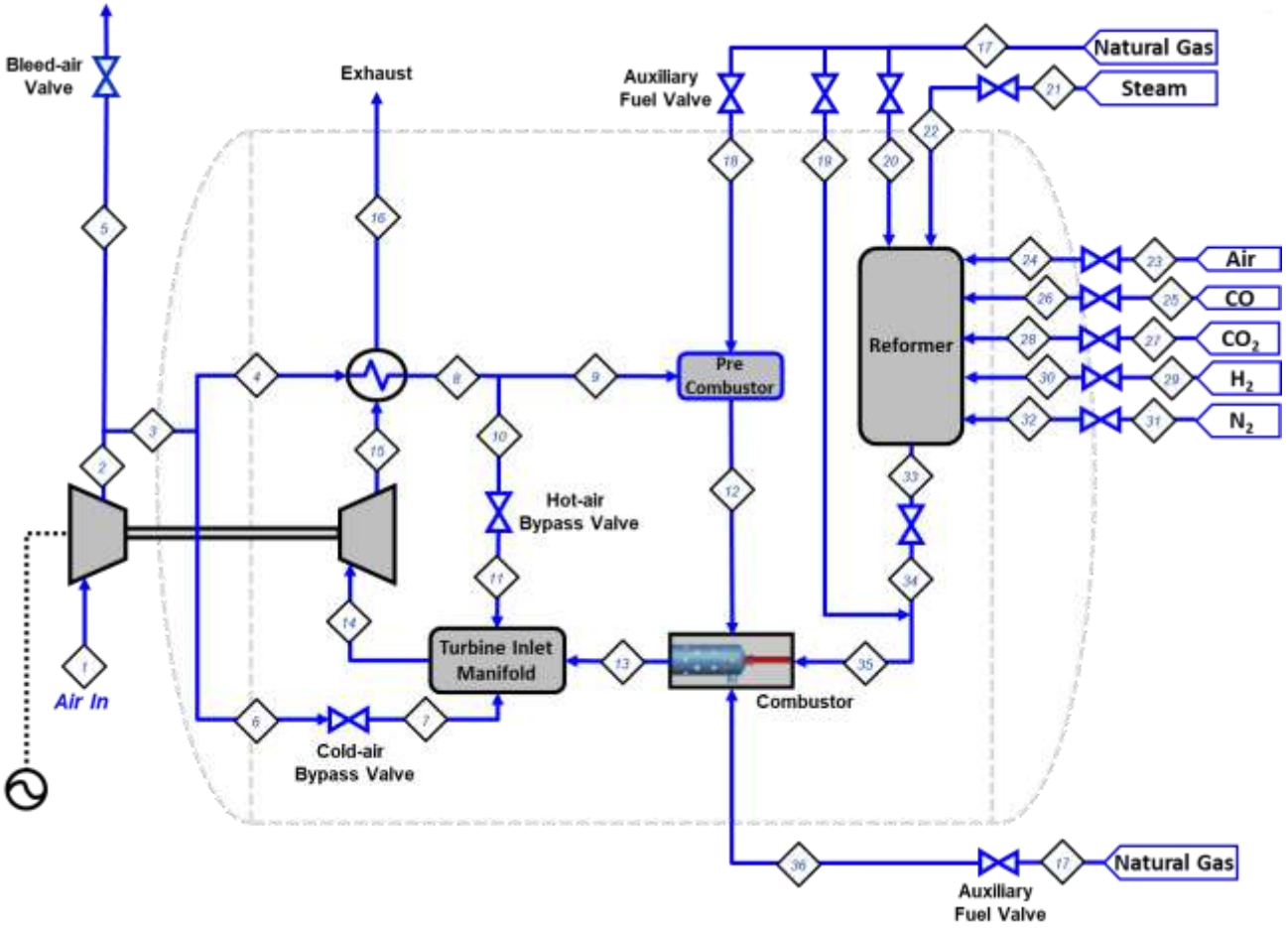
Packed bed reformer reactor



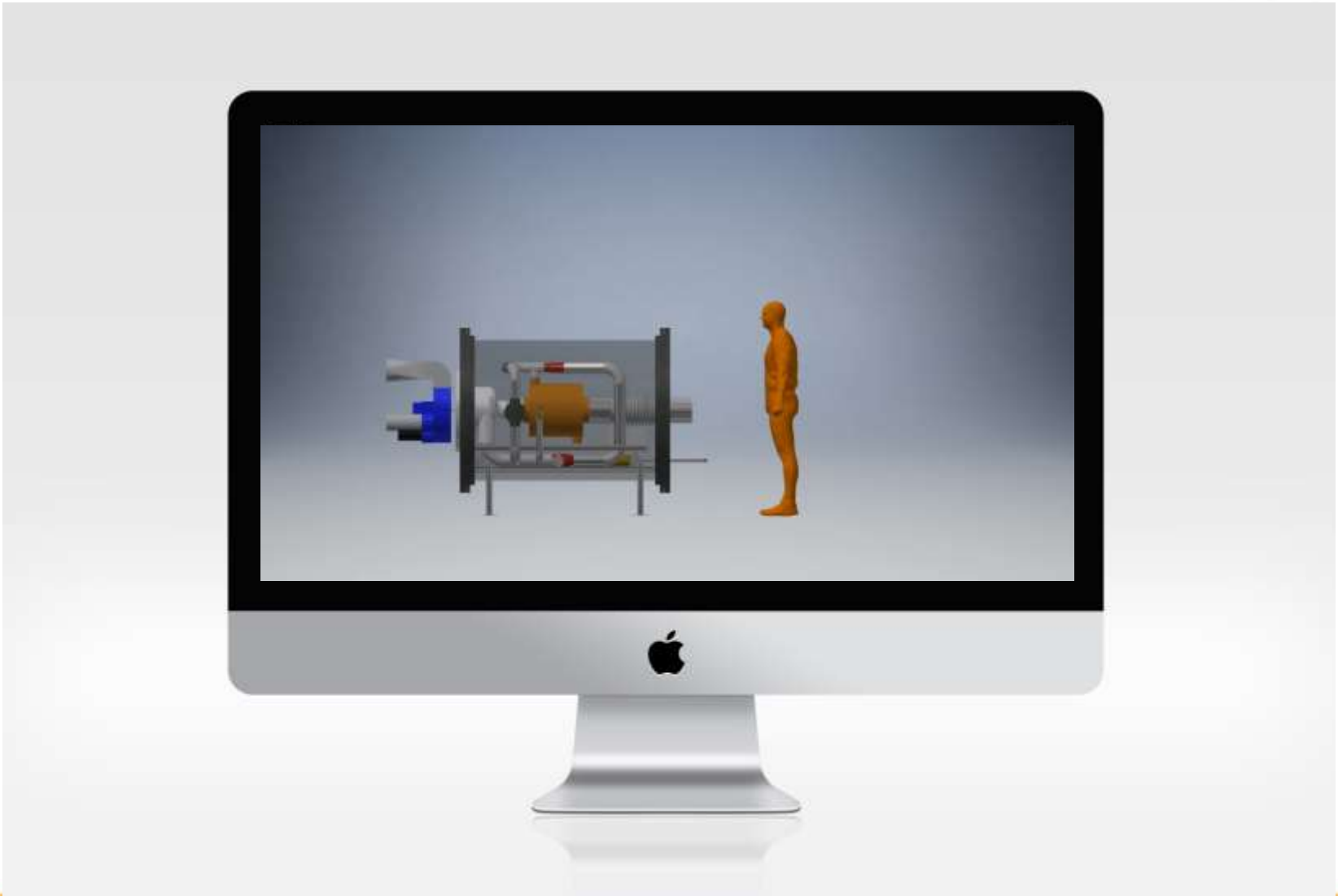


Design, Fabrication and installation of CPS Reformer

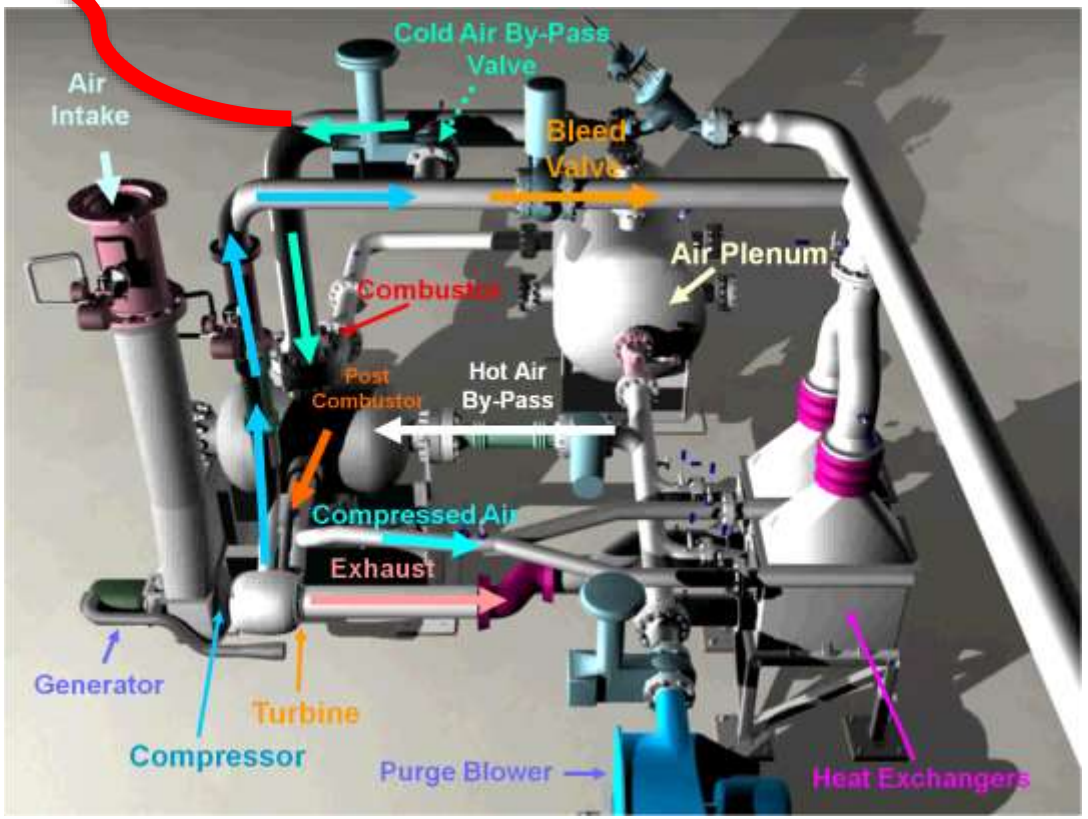
Preliminary design is completed for the CPS reformer.



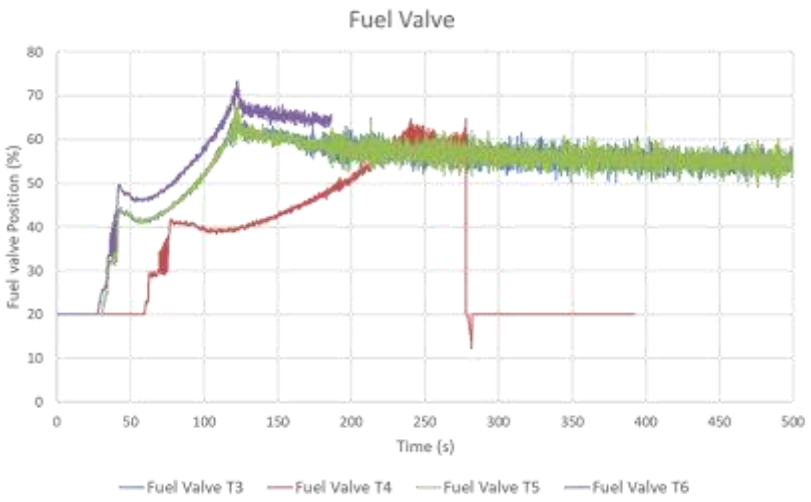
Design, Fabrication and installation of CPS Reformer

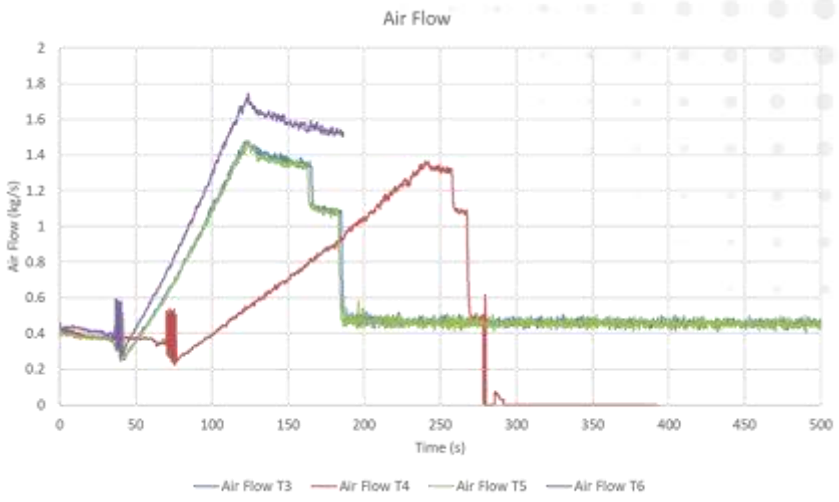


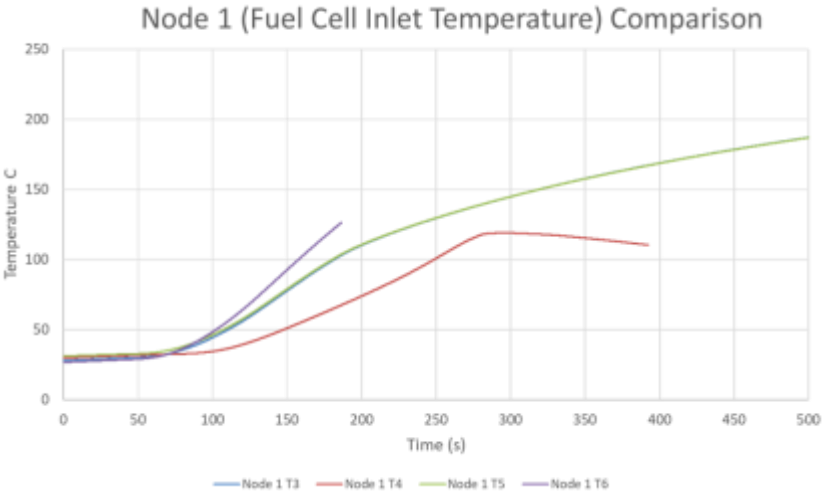
Hyper Facility Modification: Internal Combustion Engine

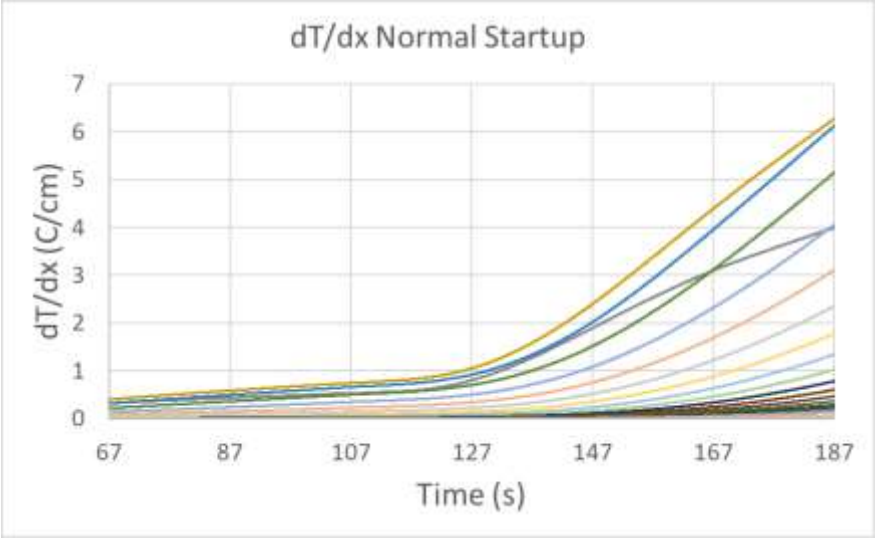


Control Strategy development：Startup









Risks

Schedule